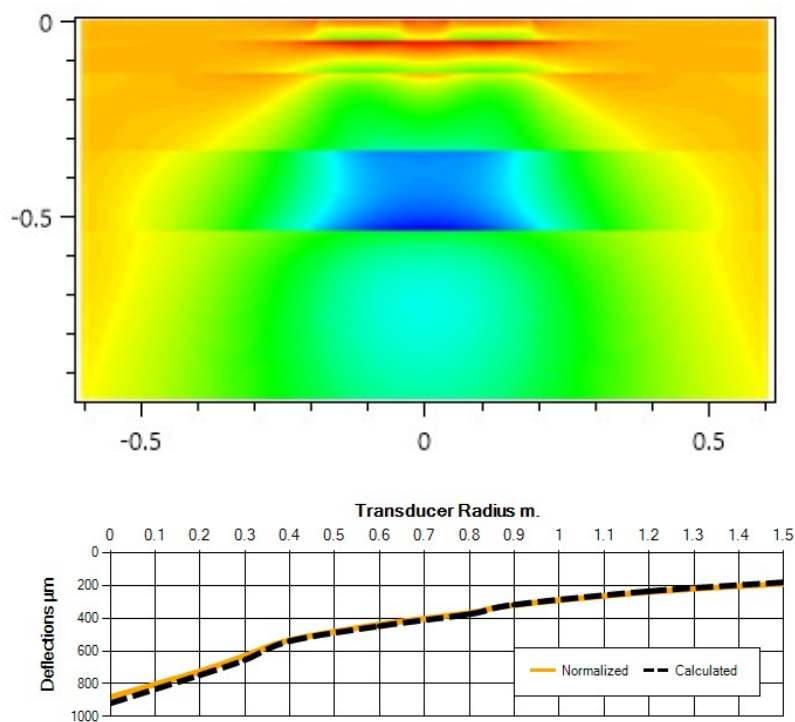


DAPS 2.0



DAPS: Deflection Analysis of Pavement Structures

**FWD Tests Backanalysis,
Design and Rehabilitation**

**Abatech Inc.
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Blooming Glen, PA 18911**

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DAPS 2.0 USER ´S MANUAL

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1.INTRODUCTION

Pavement structures provide a vital part of our transportation system. Efficient maintenance is necessary in order to achieve maximum cost benefit from the huge investment made by transportation agencies over the years. As part of maintenance planning and analysis, agencies have been making use of deflection testing equipment such as the Falling Weight Deflectometer. This type of equipment yields information regarding the structural performance in terms of deflections that are used to calculate layer stiffness modulus.

As deflection data is increasingly used to accurately define pavement response to loading, the need to develop robust backcalculation procedures has become greater. With the speed and performance of computers increasing, more mathematically intensive procedures can be used for developing solutions of large data sets.

DAPS – Deflection Analysis of Pavement Structures – is a rapid, accurate and reliable method for performing backcalculation of deflection results. A rigid base beneath the subgrade can be assumed ('bedrock'), or the subgrade can be subdivided in varying moduli layers. This is an accepted method, to some extent, to allow for known effects of non-linearity within the soil.



www.abatech.com

Figure 1 Abatech logo.

2.THEORETICAL BACKGROUND

In linear-elastic regime models, the mechanical behavior of any material is defined by two distinct parameters: the elasticity modulus E (establishes the relationship between the applied stress magnitude and the corresponding deflections or displacements), and the Poisson ratio ν (factor of comparison between the displacements that occur in two perpendicular directions). The linear-elastic mechanical behavior can be defined as being based on the principles that the materials have the ability to return to their original stress and strains states, after any given load that was previously being applied is removed, and that the strains and displacements are proportional to the forces or stresses that are being applied to the material at any given moment.

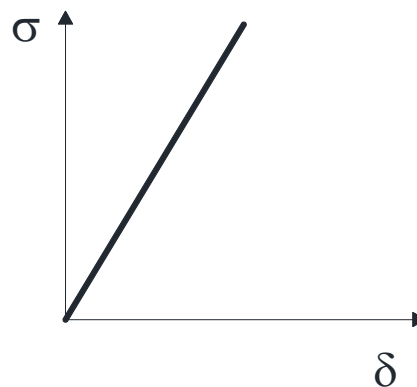


Figure 2 Linear Elastic stress / displacement relationship.

Strains and stresses relate as expressed by the generalized Hooke's Law:

$$\underline{\sigma} = \underline{D}\underline{\varepsilon}$$

In which:

$\underline{\sigma}$ - Stress vector

\underline{D} - Elasticity matrix

$\underline{\varepsilon}$ - Strain vector

Elastic models are applicable to pavement engineering in order to determine the displacements, stresses and strains that occur in pavement structures when solicited by external actions. The basic premises of these models are that the different pavement layer representative stratum's are weightless, possess infinite dimensions in the horizontal directions, and are limited in the vertical direction (by the corresponding layer thickness) except for the subgrade whose depth is assumed as infinite.

By considering a single (flexible) circular uniformly distributed load applied to an idealized pavement structure that abides by the previously stated simplifications, it is therefore possible to define the vertical alignment that coincides with the central point of the load as a revolution axis, for which every point located at equal radial distance and depth will present identical displacements, stress and strain states. The effects superposition principle can be applied in order to determine the effects of multiple loads.

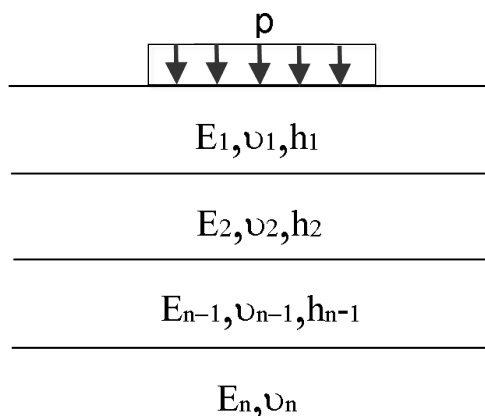


Figure 3 Axisymmetric load on idealized pavement.

Calculated displacements are used in the pavement backanalysis procedure, an iterative method that consists of determining the elastic moduli of pavement layers by comparing calculated deflections with *in situ* measured deflections.

The actual deflections are collected by performing Falling Weight Deflectometer (FWD) tests, a procedure in which a known vertical force is applied to the pavements surface, and the consequent deflections are measured and registered by a series of sensors located at previously defined distances in regard to the load center point. To replicate the constraints of the elastic models and allow their use in the backanalysis procedure, the applied force is transmitted to the pavement's surface via a circular plate.

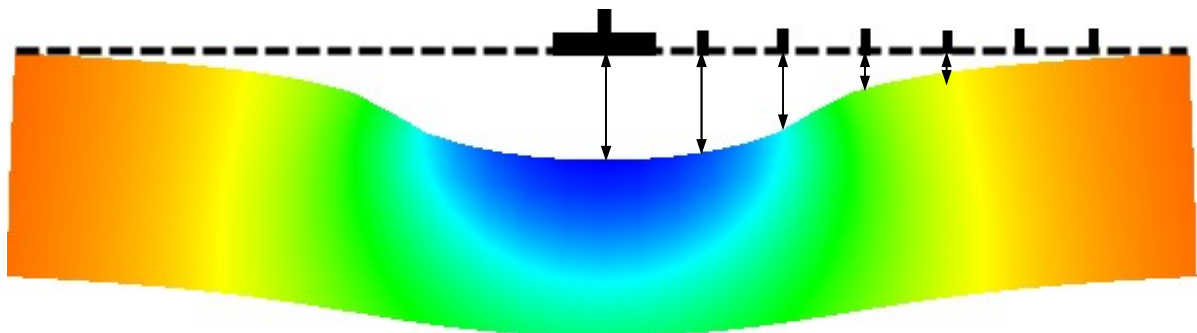


Figure 4 Falling weight deflectometer test deflection bowl.

As the distance to the center point of the load increases, the influence of the top pavement layers stiffness on the measured deflections will decrease. The set of used sensors must be selected in adequate number and spacing in order to provide information of sufficient quantity and quality to effectively define each of the tested pavement layers.

At the start of the backanalysis procedure, the thicknesses of the pavement layers are known parameters. Poisson ratios are estimated based on the used materials properties and characteristics; the moduli of the pavement layers are variables to be determined.

Given the known pavement structure and layer thicknesses, by sequentially assigning sets of varying layer moduli to the pavement and by calculating the corresponding deflections, it becomes possible to compare the calculated deflection bowl with the test measured deflection bowl and to achieve a satisfactory solution. The iterative process starts with "seed" moduli, a set of approximately defined values that are gradually refined by an optimization algorithm.

The process is interrupted when the approximation between the calculated and measured deflections proves to be a close fit. It is usual to consider as stopping criteria the root mean square **rms**. The **rms** value is calculated in accordance to the following expression:

$$RMS(\%) = \sqrt{\frac{1}{n_d} \sum_{i=1}^n \left(\frac{d_{ci} - d_{mi}}{d_{mi}} \right)^2} \times 100$$

In which:

n_d – Total number of sensors

d_{ci} – Calculated deflection at sensor index i

d_{mi} – Normalized measured deflection at sensor index i

By default, DAPS will terminate the iterative process when the **rms** criteria reaches margins of error equal or inferior to a value of 4%, but it is possible for the user to change this specific value if so desired.

3.SETUP AND USE

DAPS is designed to run in the range of Microsoft® Windows® operating systems from XP forward, in both the 32 and 64 bit PC architectures. It is distributed in a self-extracting executable file that will automatically install the software to the PC system.

DAPS is initially set with a default setup folder, but it is possible to select alternate installation locations.

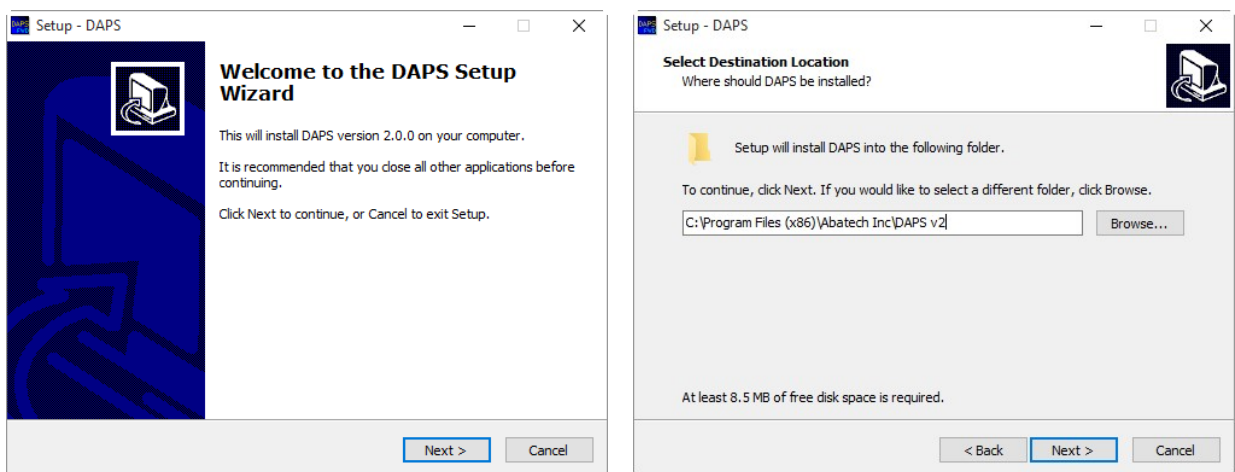


Figure 5 DAPS setup process.

The user also has the option of adding a shortcut to the Desktop. Selecting this shortcut or selecting DAPS from the list of installed programs will launch the software at any later time. When DAPS is initiated, a welcome window with some basic information will emerge, succeeded after a few seconds by the main window.

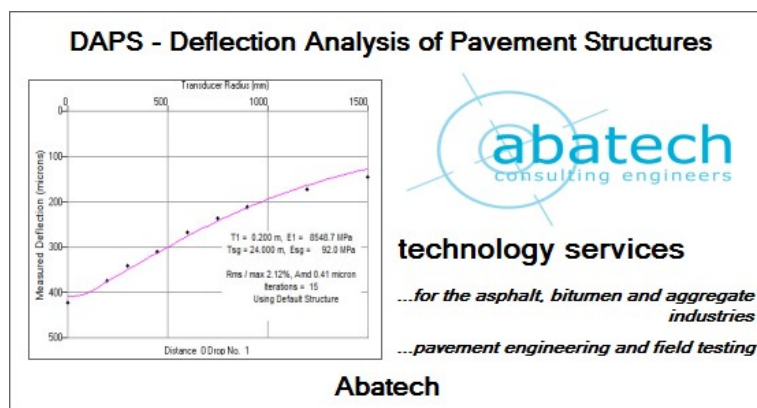


Figure 6 Splash screen.

The DAPS software is divided in two separate sections, or modules:

- **The layered elastic analysis and pavement design module**
- **The backcalculation module**

The module selection is made in the "Main" menu on the top left corner of the program window. Selecting the "DAPS Manual option" will launch a PDF file reader that will automatically load this document.



Figure 7 Main window.

DAPS is designed to function in the Metric system, input and output is made accordingly. It is possible however to load FWD test files that contain information stated in the Imperial system, but the data contained in these files will be automatically converted to Metric units before being analyzed.

DAPS considers the following set of units:

- Distances and layer thicknesses: Meters
- Deflections: Microns
- Deformability modulus: Mega Pascal
- Stress: Kilo Pascal
- Load pressure: Mega Pascal

4. ELASTIC ANALYSIS MODULE

The elastic analysis module enables the determination of stresses, strains and displacements in a pavement structure under circular uniformly distributed loads, hence making it possible to design new pavement structures or to rehabilitate existing ones. It is possible to consider a maximum of seven layers plus the subgrade, and full or partial bond (slippage) between layers.



Figure 8 Elastic Analysis module.

4.1. Pavement structure definition

The number of layers that are to be considered is defined by selecting the desired value in the "N.º of layers" field. It is initially assumed that the standard Poisson ratio value of every layer is 0.35, and that all layers are fully bonded at the contact interfaces (adhesion=100%), but these parameters can be changed at the users will. To define the pavement structure, it will be necessary to establish the modulus and thickness of each of the layers that are to be included. If the fields destined for the introduction of modulus and thickness of a layer display green backgrounds simultaneously, this fact will signify that DAPS acknowledges that particular layer as being validly defined.

When the pavement structure is correctly established, i.e. all layers are completely defined; a sequential designation and identification of the layers from top to bottom (L1-L2-L3-Ln-Subgrade) will be displayed. This fact implies that the pavement is ready to be tested.

Pavement layers cannot be defined interchangeably, i.e., DAPS will not consider as valid a structure that considers empty layer slots between validly defined layers.

Pavement Structure

Layers: 4

| | Type | E (MPa) | Poisson | h (m.) | Bond (%) |
|----|------|---------|---------|--------|----------|
| L1 | AC | 4000 | 0.35 | 0.060 | 100 |
| L2 | AC | 6000 | 0.35 | 0.080 | 100 |
| L3 | SB | 240 | 0.35 | 0.200 | 100 |
| L4 | GB | 120 | 0.35 | 0.200 | 100 |
| SG | | 60 | 0.40 | ∞ | |

Pavement Structure

Layers: 4

| | Type | E (MPa) | Poisson | h (m.) | Bond (%) |
|----|------|---------|---------|--------|----------|
| | AC | 4000 | 0.35 | 0.060 | 100 |
| | AC | 0 | 0.35 | 0.080 | 100 |
| L1 | SB | 240 | 0.35 | 0.200 | 100 |
| L2 | GB | 120 | 0.35 | 0.200 | 100 |
| SG | | 60 | 0.40 | ∞ | |

a) Valid structure

b) Invalid structure

Figure 9 Pavement structure input for the elastic analysis module.

4.2. Load definition

The elastic layered analysis module will admit loads that consist of one circular uniformly distributed area (as in the case of a FWD test), or of two circular uniformly distributed areas (as in the case of the 80 kN ESAL). The available loads in the layered elastic analysis module database will be displayed in a list. When DAPS is first installed, five different example loads will already be defined, but the user can add or delete loads at any time. To erase a load, it is necessary to select it from the list, and press the "Delete" button.

Load properties

130 KN ESAL

FWD

80 KN ESAL

AUSTROADS

MEDINA

Type: ☒ Single ☐ Dual

Designation: 130 KN ESAL

Radius (m): 0.125

Pressure (MPa): 0.662

Spacing (m): 0.375

Add
Delete

Standard Axle with two tyre contact areas

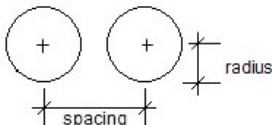


Figure 10 Load Database management.

To add a load, it is necessary to follow these steps:

1) If there is already a Load selected from the list

- Press the "Add" button
- Define the "Single" or "Dual" option (one circular load or twin circular loads)
- Define the radius, contact pressure + center distance (if dual load) and designation
- Press the "Add" button

2) If a Load is not selected

- Just like stated in 1), but without pressing the "Add" button at the beginning of the procedure.

All loads and their corresponding characteristics will be maintained from session to session. The process of defining dual or single loads is basically identical; the only difference will be that for single loads the "spacing" parameter will not be required.

4.3. Analytical analysis

If the pavement structure is properly defined with all desired layers having valid thicknesses and modulus assigned, selecting a load from the "Load List" will enable the "Run analytical analysis" button.

Load properties

130 KN ESAL
FWD
80 KN ESAL
AUSTROADS
MEDINA

Type: ☒ Single ☐ Dual

Designation: 130 KN ESAL

Radius (m): 0.125

Pressure (MPa): 0.662

Spacing (m): 0.375

Run analytical analysis Add Delete

Standard Axle with two tyre contact areas

radius

spacing

Figure 11 Enabled elastic analysis.

Pressing this button will make DAPS automatically perform the layered elastic analysis of the defined pavement structure and selected load settings.

When the analysis process is complete, the "Analytical" tab of the layered elastic analysis module will display the results that were obtained. This information will also include the detailed data of the pavement structure, namely the number of layers, as well as the mechanical and geometrical properties of each layer.

| Save to file | | | | |
|--------------|---------------|---------|---------------|----------|
| Layer | Modulus (Mpa) | Poisson | Thickness (m) | Bond (%) |
| 1 | 4000 | 0.35 | 0.06 | 100 |
| 2 | 6000 | 0.35 | 0.08 | 100 |
| 3 | 240 | 0.35 | 0.2 | 100 |
| 4 | 120 | 0.35 | 0.2 | 100 |
| SG | 60 | 0.4 | ∞ | |

Figure 12 Pavement and load information.

For DAPS to display the stresses, strains and displacements of the pavements structure critical points, the user is required to select the desired layer and also the horizontal plane that corresponds to the layer's lower or top face. For the subgrade representative layer, only the upper face depth will be available. By selecting these parameters, DAPS will automatically display the normal stresses, strains and displacements for the selected layer and depth. The critical points then depicted, will be located in the vertical alignments of the symmetry axis and of the tire center should the analysis originate in a dual load, or just in the symmetry axis otherwise.

LAYER: 2

☒ Top face
☐ Lower face

Depth: 0.139 m

Symmetry axis

Stress (kPa)

σ_x 664.09 σ_y 1337.12 σ_z -104.78

Strain (μ)

ϵ_x 38.79 ϵ_y 190.23 ϵ_z -134.2

Displacement (mm)

δ_z -0.695

Tire centre

Stress (kPa)

σ_x 1284.41 σ_y 1565 σ_z -124.98

Strain (μ)

ϵ_x 130.07 ϵ_y 193.2 ϵ_z -187.05

Displacement (mm)

δ_x 0.016 δ_z -0.675

Figure 13 Layer and depth selection.

It is not necessary to previously define the coordinates of the points for which the displacements, stresses and strains are to be known. DAPS will automatically calculate these

parameters for all points on the upper and lower faces of each layer that coincide with the vertical symmetry axis and the geometric center of the circular load.

The considered axis system is as follows:

- **X** Transverse direction
- **Y** Longitudinal direction
- **Z** Vertical direction

Should a twin load be considered, the X axis will intercept the geometric center of both circular uniformly loaded areas and the Z and Y axis will have their origin at the point in the pavements surface located halfway between the two loads.

4.3.1. File output

Pressing the "Save to file" button located on the top left corner of the "Analytical" tab window will allow the user to save the results to an ".xls" format file to a folder of his choice. The ".xls" extension will be automatically added. This file will display all of the information available for that particular pavement structure and load, as calculated by DAPS.

PAVEMENT STRUCTURE

| Layer | E (Mpa) | Poisson | Thick. (m) | Bond (%) |
|-------|---------|---------|------------|----------|
| 1 | 4000 | 0.35 | 0.06 | 100 |
| 2 | 6000 | 0.35 | 0.08 | 100 |
| 3 | 240 | 0.35 | 0.2 | 100 |
| 4 | 120 | 0.35 | 0.2 | 100 |
| SG | 60 | 0.4 | --- | --- |

DUAL LOAD DATA


Designation: 130 KN ESAL

Radius: 0.125 m

Pressure: 662 kPa

Centre Distance: 0.375 m

DAPS - ELASTIC ANALYSIS MODULE



Symmetry axis

| Layer | σ_x | σ_y | σ_z | ϵ_x | ϵ_y | ϵ_z | δz |
|-------|------------|------------|------------|--------------|--------------|--------------|------------|
| 1 | -748.48 | -1184.2 | -9.56 | -82.67 | -229.72 | 166.72 | -0.692 |
| | -337.02 | -342.16 | -37.36 | -51.05 | -52.78 | 50.09 | -0.699 |
| 2 | -462.89 | -459.74 | -40.37 | -47.97 | -47.27 | 47.09 | -0.699 |
| | 664.09 | 1337.12 | -104.78 | 38.79 | 190.23 | -134.2 | -0.695 |
| 3 | -26.61 | 0.7 | -104.3 | 40.23 | 193.81 | -396.81 | -0.695 |
| | 41.24 | 52.68 | -53.88 | 173.56 | 237.95 | -361.46 | -0.621 |
| 4 | 6.39 | 12.09 | -53.55 | 174.13 | 238.3 | -500.12 | -0.62 |
| | 20.38 | 23.31 | -31.12 | 192.59 | 225.57 | -386.76 | -0.536 |
| SG | -0.47 | 0.94 | -31 | 192.57 | 225.44 | -519.79 | -0.535 |

Tire centre

| σ_x | σ_y | σ_z | ϵ_x | ϵ_y | ϵ_z | δz | δx |
|------------|------------|------------|--------------|--------------|--------------|------------|------------|
| -1391.13 | -1607.5 | -662 | -150.02 | -223.05 | 99.23 | -0.682 | -0.023 |
| -482.94 | -533.09 | -506 | -29.81 | -46.74 | -37.6 | -0.683 | -0.007 |
| -546.32 | -613.29 | -495.84 | -26.36 | -41.42 | -15 | -0.683 | -0.006 |
| 1284.41 | 1565 | -124.98 | 130.07 | 193.2 | -187.05 | -0.675 | 0.016 |
| -11.48 | -0.06 | -123.6 | 132.51 | 196.74 | -498.18 | -0.675 | 0.017 |
| 37.73 | 49.11 | -50.21 | 158.8 | 222.83 | -335.84 | -0.599 | 0.032 |
| 5.59 | 11.28 | -49.88 | 159.19 | 223.18 | -464.89 | -0.598 | 0.032 |
| 17.74 | 21.74 | -29.03 | 169.12 | 214.06 | -357.04 | -0.52 | 0.035 |
| -1.08 | 0.84 | -28.92 | 169.12 | 213.96 | -480.3 | -0.52 | 0.035 |

Figure 14 Elastic layered analysis output file.

4.4. Graphics generation

The Elastic Analysis module also offers the possibility of generating graphics that portray the displacements, stress and strain states for a pavement under one or two circular uniformly distributed loads. This option is available after selecting the "Graphics" tab of the Elastic layered analysis module. The graphics generation tab includes three different menus:

- **Options** (to set the resolution and dimensions of the generated graphics, to save to file or copy them to the clipboard, and to enlarge/reduce the graphic window)
- **Parameter** (to switch between displacements, stresses and strains)
- **Generate graphic** (to initiate the graphics rendering process, or to clear an already existing graphics data set in order to formulate new ones)

The pavement structure that is considered for graphic generation is the same that is at the time defined for the layered elastic analysis of the pavement (4.1), but this is the only connection between these two distinct features. Before the graphics rendering process is initiated, only the "Resolution" and "Dimension" options are available (in the "Options" menu). In order to generate these graphics, DAPS will first create a grid of points that will cover a predetermined area of the pavement's transverse section along the X axis.

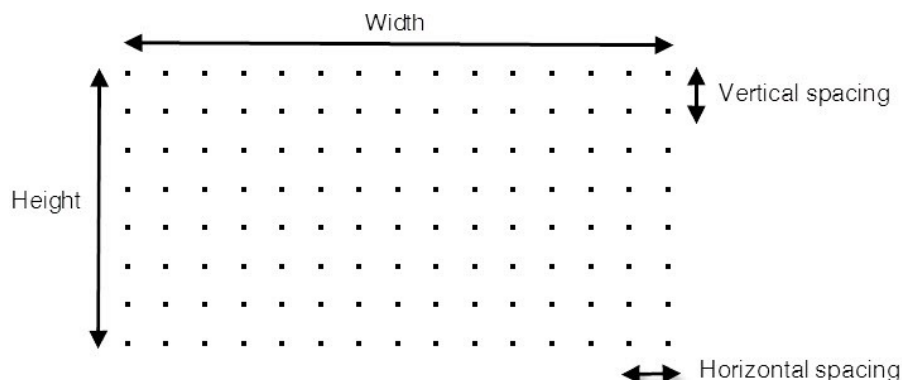


Figure 15 Grid scheme.

The "Resolution" option will define the horizontal and vertical spacing of the grid, and the "Dimension" option will define the width and height (horizontal and vertical dimensions) of the area that will be covered by the graphics.

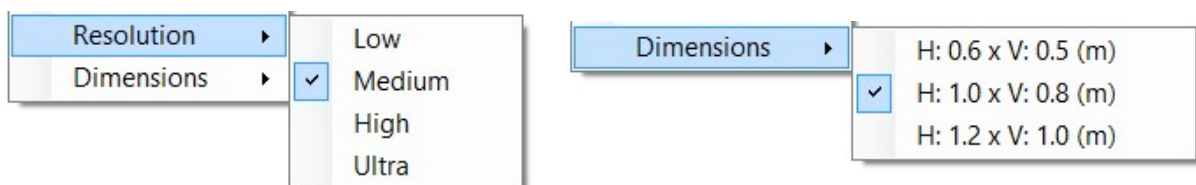


Figure 16 Selection of graphics resolution and dimension.

The time required for DAPS to complete the graphics rendering process depends on the resolution and dimension settings, but also on the hardware performance of the PC that is running the program and on the number of layers that are being considered. The better the resolution and the larger the selected area, the longer the process will take.

Using the "Ultra" resolution will be time consuming, given the fact that this option will assume a grid of points separated by just one millimeter in both the horizontal and vertical directions. The "Ultra" resolution, combined with a dimension of 1.0 x 0.8 meters, will therefore result in several hundred thousand points for which DAPS will have to calculate stresses, strains and displacements before rendering the corresponding graphics.

The program initially considers as standard the "Medium" resolution and an area of 1.0 meter in width by 0.8 meters in depth. To generate the graphics, the user has to select the "Graphic generation" menu and select a load from the list that will be made visible by pressing the "Select load to use" option. These loads will coincide exactly with those that are listed in the previously described Load Database (4.2), but will only be available if a valid pavement structure is already validly defined (4.1).

Selecting a load will initiate the process of graphic generation; a progress bar will become visible in order to let the user be aware of the graphics rendering process evolution.



Figure 17 Graphic generation: load selection and progress bar.

When the graphics rendering process is complete, DAPS will automatically display the corresponding graphic accordingly to the Parameter (stress/strain/displacement) and direction (transverse/longitudinal/vertical) that is selected in the corresponding menus.

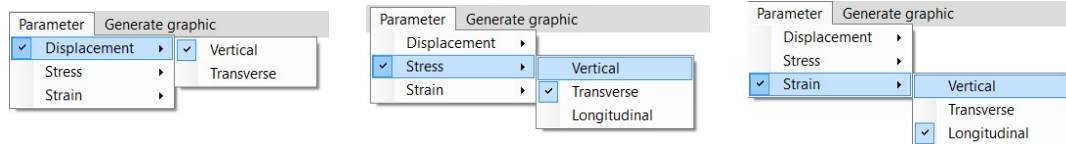


Figure 18 Selection of Viewing parameters and directions.

Each point will then be depicted using a color spectrum that relates the magnitude of the selected parameter in each particular coordinate to the maximum and minimum values calculated for the entire pavement section. On the right side of the graphic there will be a color scale, and the corresponding numerical values. Higher magnitude values are represented by the red color, while lower magnitude values will be represented by the blue color.

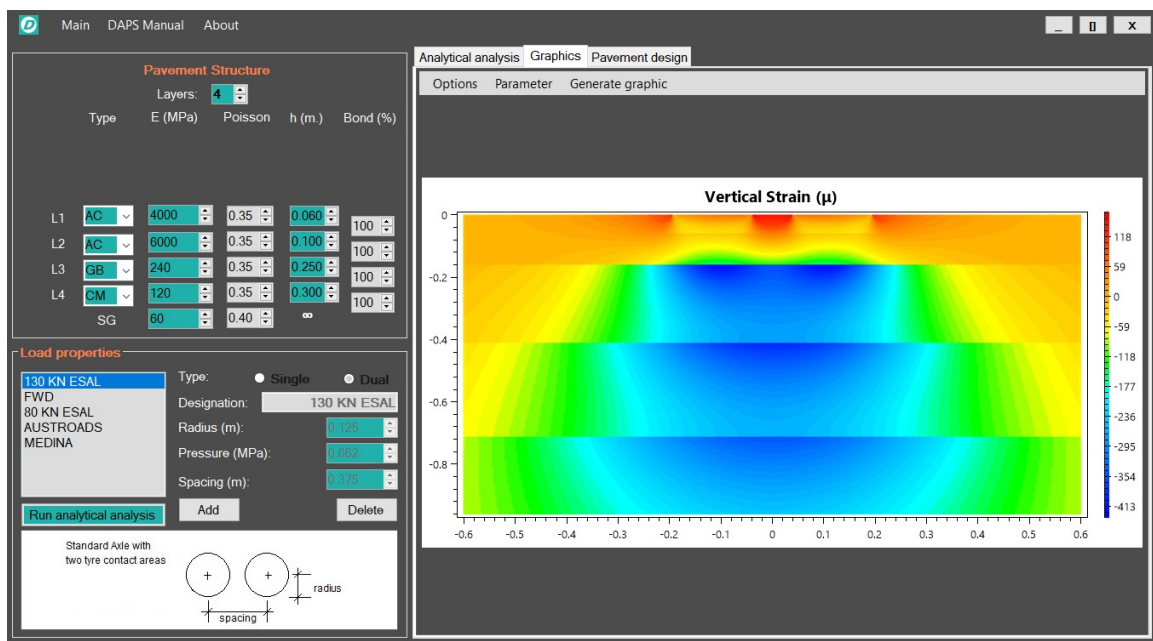


Figure 19 Generated graphic example.

After completion of the graphics generation process the "Resolution" and "Dimension" options will no longer be available because these options can only be set before the process starts, but the "Full Window" item will now be available, along with the "Save to File" option. Using the "Save to file" item allows the user to save a ".bmp" file of the graphic that is being visualized at that particular moment. By selecting the "Copy to clipboard" option, the graphic will be made available to be pasted directly in any other compatible document (text file, spreadsheet, etc...).

Checking the "Full Window" item of the "Options" menu, will enlarge the graphic to the full size of the DAPS window. Should DAPS be maximized when the "Full Window" item is selected, this action will make the graphic occupy 100% of the screen.

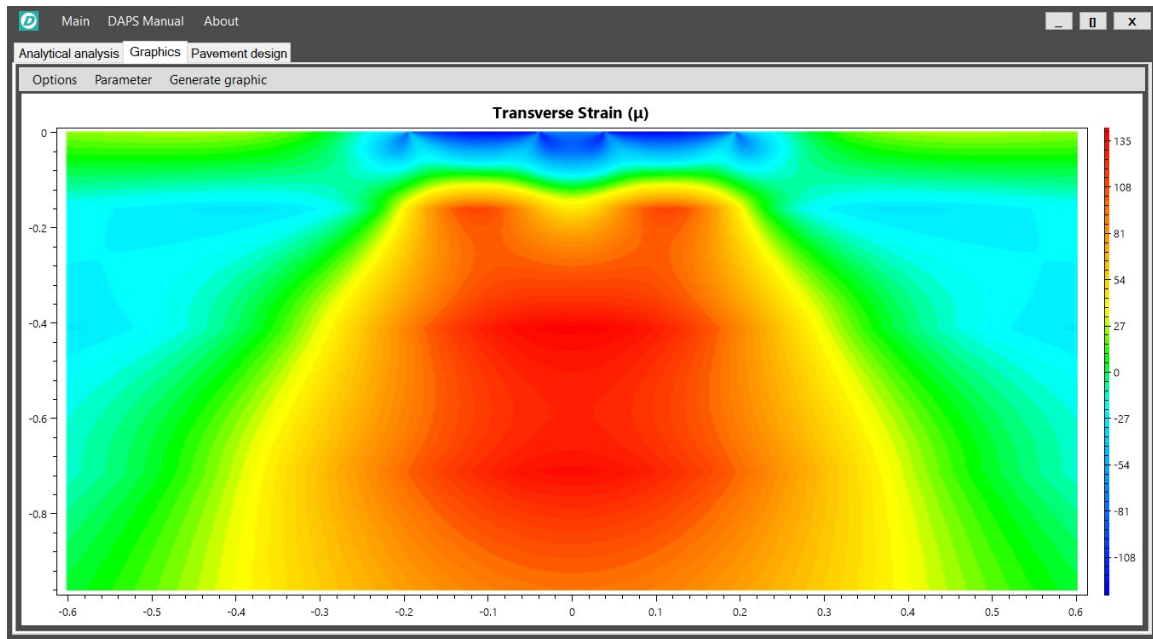


Figure 20 Enlarged graphic.

To switch back to the standard window format, it is required to uncheck the "Full Size" option, thus returning to the original layout. To initiate another graphics generation process (with other pavement structure, load, resolution or dimensions) it is first required to clear the existing graphic data by using the "Reset" option of the "Graphic generation" menu. This action will make the "Resolution" and "Dimension" option available once more.

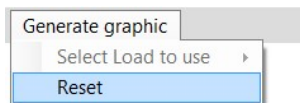


Figure 21 Graphics reset.

It is possible to use the elastic analysis module to calculate displacements stresses and strains while the program is in the process of generating graphics, even with other loads or different pavement structures. It is also possible to use the features of the Backcalculation module while the graphics generation process is underway.

4.5. Flexible pavement design and rehabilitation

In order to use the DAPS flexible pavement design features, it is mandatory to first complete the pavement structure definition with a valid input (complete layer modulus and thickness data) and also to assign the material type that corresponds to each layer. The subgrade is automatically identified; in regard to the other layers, there are five possible options:

- **CM** Cemented materials
- **AC** Asphalt concrete
- **PC** Portland cement concrete
- **GB** Granular base
- **SB** Granular sub-base

Only by assigning the material type can DAPS identify the structures critical points, and evaluate if the correspondent strains and stresses are compatible with the expected traffic and intended life span. To access the pavement design capabilities, it is necessary to select the "Pavement design" tab of DAPS elastic module. Please note that the pavement design features will always consider full adhesion between the considered pavement layers.

4.5.1. Weather input

The climatic conditions of the location in which a pavement is built plays a pivotal role in the performance and longevity of the structure, given the fact that layers that are comprised of bituminous materials have their deformability modulus highly dependent on the fluctuations of the environments temperature. In order to account for these variations, DAPS offers the possibility of including in the pavement design process an automatic method to determine asphalt concrete layers moduli in regard to climatic data.

With this specific goal in mind, DAPS resorts to the largest weather station database available online, the National Oceanic and Atmospheric Administration (NOAA) database:

<https://www.ncdc.noaa.gov/cdo-web/datatools/selectlocation>

NOAA's database includes extensive data on weather stations of every country in the world; it is of public access and offers a very simple process to obtain the desired information. When accessing the database, the initial information that has to be selected is in the following order:

DataSet: **Daily Summaries** >> Location Type >> **Country** >> Select a Country

When the desired country has been selected, the list of available weather stations/locations is automatically displayed. To proceed to the next step, it is necessary to choose the desired weather station/location by clicking on the corresponding "ADD TO CART" button.

Following this action, it is required to press the "Cart (Free Data)" button that becomes enabled on the top right corner of the web browsers page.

Select a Dataset: Daily Summaries, Global Summary of the Month, Global Summary of the Year, Normals Annual/Seasonal, Normals Daily, Normals Hourly, Normals Monthly

Select a Location Type: Country, US Territory, State, County, Zip Code

Select a Country: Afghanistan, Albania, Algeria, Angola, Antarctica, Antigua & Barbuda, Argentina

Daily Summaries > Country > Angola

1-7 of 7

STATION DETAILS

LUANDA, AO
View Full Details
Station ID: GHCHD-AO000066160
Period of Record: 1960-04-01 to 2019-09-24

LUBANGO SA DA BAND, AO
View Full Details
Station ID: GHCHD-AO000066390
Period of Record: 1957-09-03 to 2019-09-24

MAVINGA, AO
View Full Details
Station ID: GHCHD-AO000066447
Period of Record: 1957-07-02 to 1975-09-22

MENONGUE SERPA PIN, AO
View Full Details
Station ID: GHCHD-AO000066410
Period of Record: 1957-07-03 to 1981-09-17

Figure 22 NOAA weather station database (step 1).

The next step is defining the format of the desired data as "Custom GHCN-Daily CSV" and defining the start and end dates of the time range for which we would like to obtain information, then click on the "CONTINUE" button on the lower right corner of the web browsers page.

GHCN-Daily PDF
DOC Certification Option
(Does not include all elements)
☐ Include Documentation

Custom GHCN-Daily CSV
(Additional options available on next page)

Custom GHCN-Daily Text
(Additional options available on next page)

Select the Date Range
Click to choose the date range below.
1960-04-01 to 2019-09-24

Review the items in your cart [CLEAR CART]

LUANDA, AO
View Full Details
Station ID: GHCHD-AO000066160
Period of Record: 1960-04-01 to 2019-09-24

CONTINUE

Figure 23 NOAA weather station database (step 2).

It is then necessary to check the following options:

Station Name >> Geographic location >> Metric units >> Air temperature

Station Detail & Data Flag Options

Additional output options such as data flags (attributes), station names, and geographic location are also available.

☒ Station Name
☒ Geographic Location
☐ Include Data Flags
 Units Metric

Select data types for custom output

The items below are data types that can be added to the output. Expand the data type category headers to view the categorized data type names and descriptions.

Show All / Hide All | Select All / Deselect All

☐ Precipitation
☒ Air Temperature

☒ Average Temperature (TAVG)
☒ Maximum temperature (TMAX)
☒ Minimum temperature (TMIN)

BACK
CONTINUE

Figure 24 NOAA weather station database (step 3).

Continuing to the next and final phase of the process, it will be necessary to enter an e-mail address to which a download link of the data file with the selected information will be sent by NOAA. After the data file has become available, by selecting the Options > Open NOAA weather station data file, the corresponding data will be interpreted and displayed by DAPS.

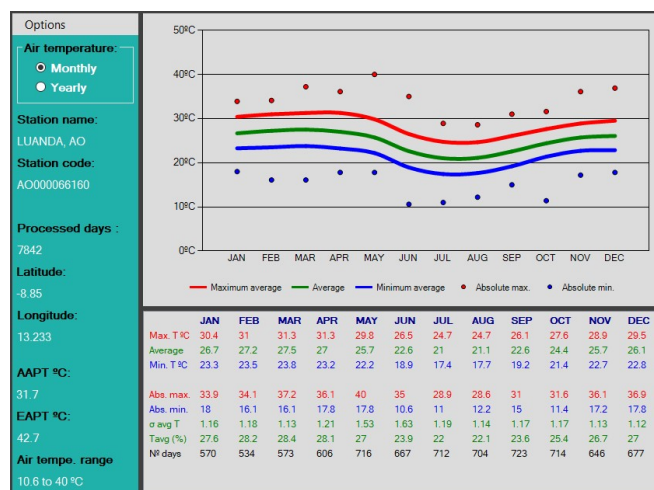


Figure 25 Graphic and numerical data summary of a NOAA data file.

Should the location for which the pavement structure is intended not be listed in NOAA's database but there exists an alternate source for this information, DAPS will accept data in the form of a pre-defined ".xls" file, in which it is necessary to establish the averages of the maximum, mean and minimum monthly temperatures. This file is made available by selecting the "Create user made weather file" option, and loaded by DAPS after having selected the "Open user made weather file" option.

| | JAN | FEB | MAR | APR | MAY | JUN | JUL | AUG | SEP | OCT | NOV | DEC |
|------------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| Maximum °C | | | | | | | | | | | | |
| Average °C | | | | | | | | | | | | |
| Minimum °C | | | | | | | | | | | | |

Figure 26 User made weather data file creation.

There are three possible different forms for which DAPS can factor in weather information on a pavement design or rehabilitation study:

- **Yearly data:** DAPS will consider the Annual Average Pavement Temperature (AAPT) as the design temperature of all asphalt concrete layers.
- **Yearly data (2 factors):** AAPT is used to determine the rutting criteria verification and the Equivalent Annual Pavement Temperature (EAPT) for asphalt concrete layers fatigue.
- **Monthly data:** For each month, DAPS determines a representative air temperature, the design temperature for asphalt layers is calculated as function of this particular value and the depth at which it is located on the pavements structure.

The definition of these variables is as follows:

$$\mathbf{EAPT} = \mathbf{AAPT} + 11 \text{ (}^{\circ}\text{C)}$$

$$\mathbf{AAPT} = \frac{\sum_{i=1}^{12} \mathbf{MMPT}}{12} \text{ (}^{\circ}\text{C)}$$

$$\mathbf{MMPT} = \text{Monthly mean pavement temperature (MMPT=1.15} \times \mathbf{MMAT} + 3.17, \text{ }^{\circ}\text{C)}$$

$$\mathbf{MMAT} = \text{Monthly mean air temperature (}^{\circ}\text{C)}$$

$$\mathbf{T \text{ at pavement depth } z} = \mathbf{AirT} \times \left(1 + \frac{1}{z+4} \right) - \frac{34}{z+4} + 6 \text{ (Fahrenheit, inches)}$$

The temperatures that are used in the monthly design procedure are defined as a percentile of the average temperatures recorded for each particular month in case the data is provided by a NOAA file (this percentile value is user defined in the "Temperature percentile to consider" option and can vary between 50.00 and 99.99%, the considered standard value is 80%); it will be the average temperature of the month, should the data originate from a user made ".xls" file.

4.5.2. Asphalt concrete layers binder and mix properties

After having successfully defined the pavement structure information (number and type of layers, thicknesses and moduli), by accessing the "AC properties & design variables" tab of the Pavement design module, it becomes possible to further establish the properties of both the bituminous binder and mix properties that will be taken in consideration by DAPS to determine asphalt concrete layers moduli. It should be noted, that these properties will only be effectively considered when designing a pavement with weather input (and therefore asphalt layer moduli variation as a function of temperature) and that the number of AC layers in the pavement structure is limited to a maximum of 3.

| Layer | Type | E (MPa) | Poisson | h (m.) | Bond (%) |
|-------|------|---------|---------|--------|----------|
| L1 | AC | 2845 | 0.35 | 0.050 | 100 |
| L2 | AC | 3256 | 0.35 | 0.100 | 100 |
| L3 | GB | 450 | 0.35 | 0.300 | 100 |
| L4 | CM | 225 | 0.35 | 0.300 | 100 |
| SG | | 60 | 0.40 | | |

| Criteria | Method | Value |
|----------|---------|-------------|
| 10 | 1.840E1 | f1 6.167E-5 |
| 12 | 3.291E0 | f3 8.540E-1 |
| 14 | 4.840E0 | f5 6.900E-1 |

Figure 27 AC properties & design variables tab.

For each asphalt concrete layer, it then becomes necessary to define the following variables:

- **TPen** : Temperature at which the binder was subjected in the penetration test (°C)
- **Pene** : The penetration achieved in the above described test (dmm)
- **Trb** : The binders ring and ball test temperature (°C)
- **Vv** : The volume of voids in the mix (%)
- **Vb** : The volume of binder in the mix (%)

The information that is used to define each AC layer can be saved to file and used posteriorly, in order to facilitate and expedite the AC layer characterization process.

In the "AC properties & design variables" tab, there exists an auxiliary section that simulates the variation in moduli of both binder and mix as a function of air/pavement temperature, depth of the layer, and the previously described binder and mix variables. This auxiliary section intends to allow to experiment with different binder/mix combinations and to help define the properties that better adjust to the environmental conditions of each possible pavement location.

The auxiliary section, displays the results for the automatic binder/mix moduli determination methods that DAPS offers, namely, van der Poel and Shell for binder; Bonnaure, Shell and Nottingham University for mix.

It should be noted that all these methods, just like any others, have their limitations. For example, the listed mix moduli prediction methods are intended to be used when the binder stiffness is equal or higher than 5 MPa. The methods that are used by DAPS as standard, are the van der Poel and Bonnaure methods. Changing this selection, along with the layer depth at which temperatures, binder stiffness and mix stiffness are determined is possible by using the options of the following menu:

Binder stiffness Mix stiffness AC moduli @

Figure 28 Menu for binder/mix method and temperature depth selection.

Abatech makes available for free download the software BitPropsV2, a standalone program that mimics the van der Poel and the Bonnaure nomographs, as considered by DAPS.

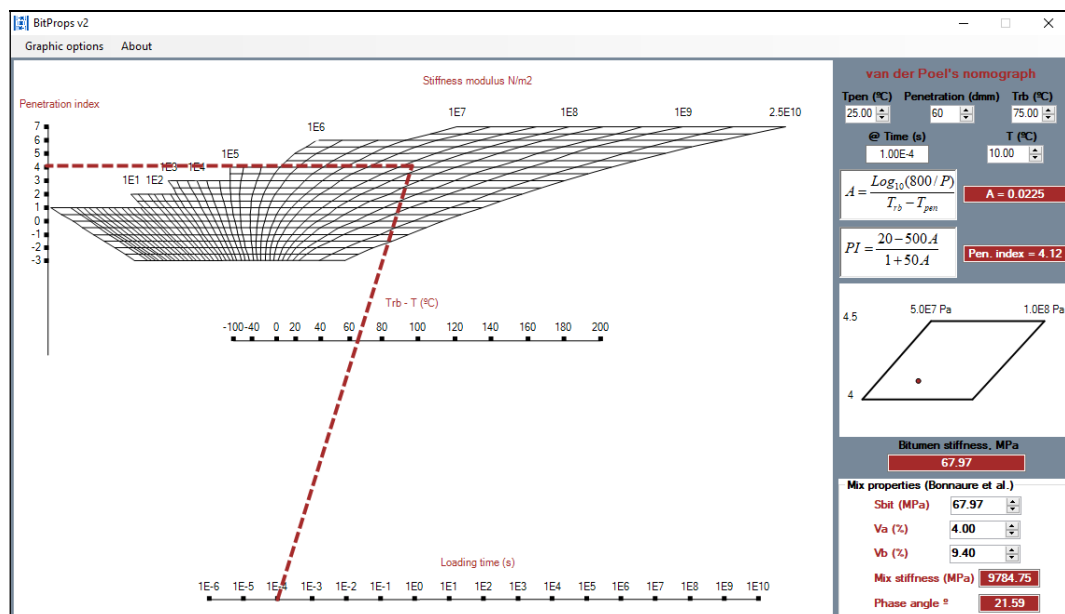


Figure 29 BitPropsv2 software.

The download link for BitPropsV2 is: <https://abatech.sharefile.com/d-s0e488d2caf84d9da>

The Shell binder stiffness prediction method is defined as:

$$S_b = 1.157 \times 10^{-7} \times t^{-0.368} \times 2.718^{-IP} \times (T_{rb} - T)^5$$

$$IP = \frac{1951 - 500 \times \log Pene - 20 \times T_{rb}}{500 \times \log Pene - T_{rb} - 120.1}$$

While for mix stiffness:

$$S_m = S_b \times \left(1 + \frac{2.5}{n} \times \frac{C_v}{1 - C_v} \right)^n$$

$$n = 0.83 \times \log \left(\frac{4 \times 10^4}{S_b} \right)$$

$$C_v = \frac{V_a}{V_a + V_b}$$

The Nottingham University mix stiffness prediction method is:

$$S_m = S_b \times \left[1 + \frac{257.5 - 2.5 \times VMA}{n \times (VMA - 3)} \right]^n$$

$$n = 0.83 \times \log \left(\frac{4 \times 10^4}{S_b} \right)$$

$$VMA = V_v + V_b$$

4.5.3. Traffic loads and repetition

The design load that is considered by DAPS in order to determine if the structure's maximum strains and stresses are compatible with the expected life span, is the one that is selected in the "Load properties" section of DAPS (4.2) at the moment of verifying the design criteria. The number of design load repetitions to be considered is defined and adjusted by assigning the desired value in the "Load repetitions" options located in the lower right section of the "AC properties & design variables" tab. The design speed, and consequentially loading time, can also be adjusted in this area.

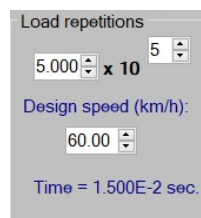


Figure 30 Load repetitions and design speed.

Loading time is one of the variables required to determine binder stiffness. Its value is defined as a function of the design speed and load diameter, and automatically calculated when either of these two variables is modified.

$$Time(sec) = \frac{Load \phi}{Speed \times 1000 / 60^2}$$

4.5.4. Design criteria

The flexible pavement design and rehabilitation module considers 3 different design criteria:

- Asphalt concrete fatigue
- Cemented materials fatigue
- Subgrade rutting

The methods on which each criteria evaluation is to be determined based on the pavement structure properties and load repetition, are accessible in the lower central section of the "AC properties & design variables" tab. The numerical functions accessible in this menu are used for the definition of the maximum possible number of load repetitions to failure of each of the 3 mentioned criterions, and are selectable by the user from a wide variety of choices. The numerical parameters of each method can also be completely adjusted and changed.

| Criteria | Method |
|---|------------------------|
| AC fatigue: Asphalt Institute | |
| $N_f = f_0 \cdot (10^M) \cdot (f_1 \cdot \epsilon_t^{-f_2}) \cdot (E^{-f_3})$ | f0 1.840E1 f1 6.167E-5 |
| $M = f_4 \cdot (\frac{V_b}{V_v + V_b} - f_5)$ | f2 3.291E0 f3 8.540E-1 |
| | f4 4.840E0 fs 6.900E-1 |

Figure 31 Design criteria, methods and parameters definition.

The available options, accordingly to the corresponding origin/method are:

For asphalt concrete fatigue:

$$N_f = f_0 \cdot (10^M) \cdot (f_1 \cdot \epsilon_t^{-f_2}) \cdot (E^{-f_3})$$

Asphalt Institute:

$$M = f_4 \cdot (\frac{V_b}{V_v + V_b} - f_5)$$

Shell:

$$N_f = \left(\frac{\epsilon_t}{(s_1 \cdot V_b + s_2) \cdot E^{-s_3}} \right)^{-1/s_4}$$

$$\text{United Kingdom - TRL: } N_f = u_1 \cdot 10^{-10} \cdot \left(\frac{1}{\varepsilon_t} \right)^{u_2}$$

$$\text{Belgium - BRRC: } N_f = b_1 \cdot 10^{-14} \cdot \left(\frac{1}{\varepsilon_t} \right)^{b_2}$$

$$\begin{aligned} N_f &= i_1 \cdot (10^{M-4}) \cdot (\varepsilon_t^{-i_1}) \cdot (E^{-i_2}) \\ \text{India - IRC: } M &= i_3 \cdot \left(\frac{V_b}{V_v + V_b} - i_4 \right) \end{aligned}$$

$$\text{AustRoads: } N_f = RF \left[\frac{a_1(a_2 V_b + a_3)}{S_{mix}^{a_4} \varepsilon_t} \right]^{a_5}$$

For cemented materials fatigue:

$$\text{Illinois University: } \log_{10} N_c = i_1 - i_2 \cdot \left(\frac{\sigma}{M_r} \right)$$

$$\text{India - IRC: } N_c = RF \left[\frac{i_1 / Sm^{i_2} + i_3}{\varepsilon_t} \right]^{i_4}$$

$$\text{MEPDG - 2008: } \log_{10} N_c = \frac{m1 - \frac{\sigma}{Mr}}{m2}$$

$$\text{AustRoads: } N_c = RF \left[\frac{a_1 / Sm^{a_2} + a_3}{\varepsilon_t} \right]^{a_4}$$

$$\text{Jordan: } \log_{10} N_c = j_1 \cdot \left(1 - \frac{\varepsilon_t}{j_2 \cdot j_3} \right)$$

$$\text{Portugal - JAE: } \log_{10} N_c = \left(1 - \frac{\sigma}{Mr} \right) / a$$

For subgrade rutting:

Asphalt Institute: $N_r = \left(\frac{k}{\epsilon_v} \right)^{1/m}$

Shell: $N_r = \left(\frac{k}{\epsilon_v} \right)^{1/m}$

United Kingdom - TRL: $N_r = u_1 \cdot \left(\frac{1}{\epsilon_v} \right)^{-u_2}$

Belgium - BRRC: $N_r = b_1 \cdot \left(\frac{1}{\epsilon_v} \right)^{-b_2}$

India - IRC: $N_r = i_1 \cdot 10^{-8} \left(\frac{1}{\epsilon_v} \right)^{i_2}$

AustRoads: $N_r = \left(\frac{a_1}{\epsilon_v} \right)^{a_2}$

Additional methods can be included in DAPS easily, so should there be any other that you would like to see added to DAPS features, please contact us (sraposo@abatech.com) with the corresponding information.

4.5.5. New design

Having defined the pavement structure, the weather data (if any), the load characteristics and the preferred design criteria methods, DAPS is ready to evaluate the compatibility of the pavement structure with the expected load repetition/intended life span; so it becomes possible to select the "Flexible" tab of the Pavement Design options and to define the intended design type.

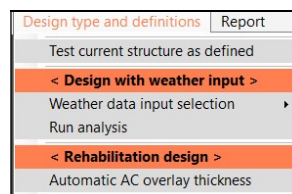


Figure 32 Design type and definitions options.

The simplest possible design type, is the one in which weather input is not considered, and that therefore, the only requirement is to test the structure that is defined in the "Pavement structure" section (4.1), calculate the strains and stresses at the critical points (automatically determined by the DAPS algorithm), and compare the expected load repetitions with the maximum allowed ones as determined by the criteria methods.

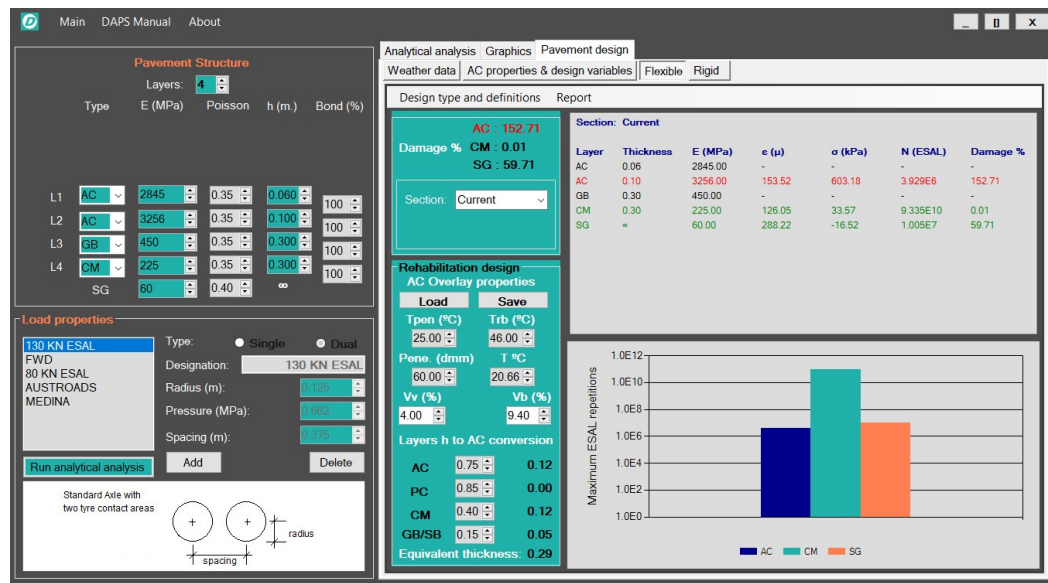


Figure 33 Current pavement structure design test.

The results become visible immediately, both in graphic and numerical form. All of the pavement data, including layers structure and calculated strains/stresses/maximum allowable repetitions will be displayed. If the design criteria are met, the damage percentages (ratio between the expected and maximum repetitions) will be shown in green color, otherwise they will be displayed in red. A graphic in which the maximum repetitions as calculated by each design criteria are depicted and compared will also be available.

Should the intended design type selection require weather input in multiple calculations (Yearly 2 factors or Monthly design types), the numerical data that relates to each specific section (2 yearly temperatures or 12 monthly temperatures) is selected using the drop down list. In these cases, the damage to the structure will be the combined sum of the damages calculated for each individual section and is automatically displayed above the drop down list. For the monthly temperatures design procedure, it also becomes possible to visualize charts in which the maximum allowable load repetitions for each month are displayed.

If the design proves to be not satisfactory, it is possible to adjust the pavement structure (layer number and type, thicknesses, moduli, etc...) and again run the design procedure in order to verify if the modified structure is then compliant with the design criteria and expected load repetitions. DAPS automatically recalculates asphalt concrete layers moduli based on the new depths (therefore temperatures), and the consequent stresses and strains.

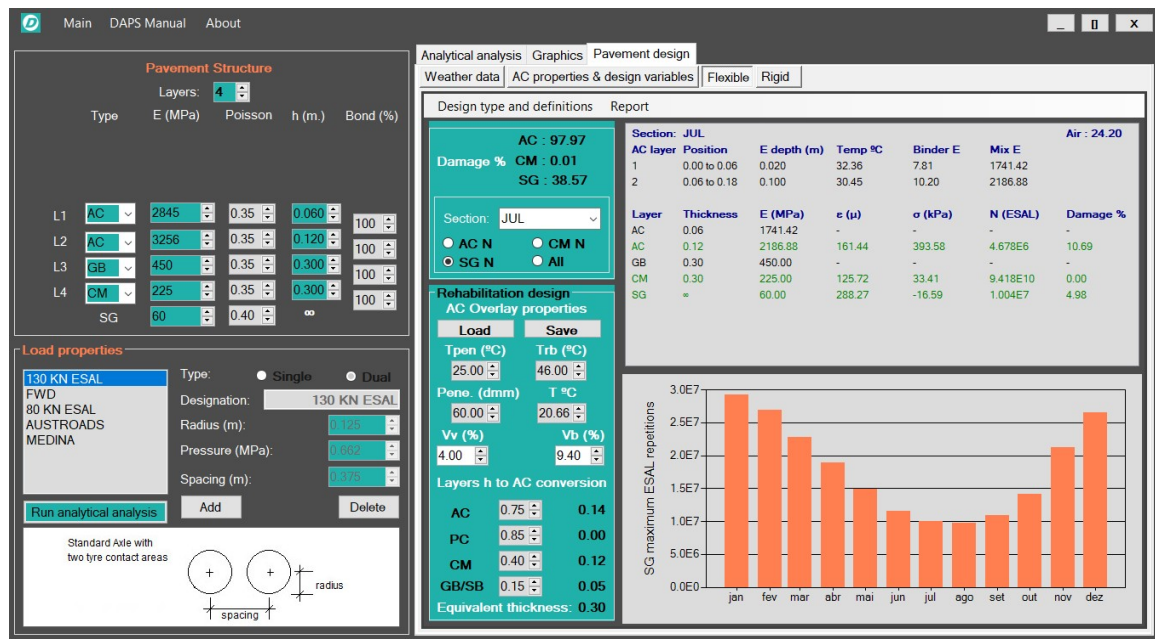


Figure 34 Monthly pavement design type example.

4.5.6. Rehabilitation design

DAPS allows to perform pavement rehabilitation design, by using the “effective thickness” method, which consists of converting all of the existing pavements layers (as defined in the pavement structure area [4.1]) to a unique asphalt concrete layer. During the rehabilitation design process, DAPS will iteratively add one centimeter to the “converted” asphalt concrete layer, until both the asphalt fatigue and subgrade rutting criteria are met. The process of converting existing pavement layers to the rehabilitation design asphalt concrete layer depends on their corresponding type (material) and level of deterioration. A conversion factor is applied to the thicknesses of the existing layers; the sum of these individual layer converted thicknesses will then become the initial thickness of the “converted” rehabilitation design asphalt concrete layer.

The thickness conversion factors to be applied to existing pavement layers are in the range:

- **Asphalt concrete layers:** 0.3 to 1.0
- **Portland cement concrete layers:** 0.3 to 1.0
- **Cemented material layers:** 0.3 to 0.5
- **Granular layers:** 0.1 to 0.2

The mix properties of the “converted” asphalt concrete layer have to be previously defined, as well as a target pavement temperature that will be used for determining binder and mix stiffness (except if a design type with weather input has been selected, in which case the temperatures that are representative of the chosen location will be considered for this purpose). All design types considered for “New design” are also available for rehabilitation design, namely yearly temperature (AAPT), yearly temperature two factors (AAPT & EAPT) and monthly temperature design.

After the rehabilitation design process is completed, the numerical data that will be displayed will show a pavement structure comprised of two asphalt concrete layers. The asphalt concrete overlay thickness (of a mix with the properties as defined in the “Rehabilitation design” section), is that of the surface layer (the second AC layer corresponds to the initial thickness of the existing pavement converted to a unique AC layer).

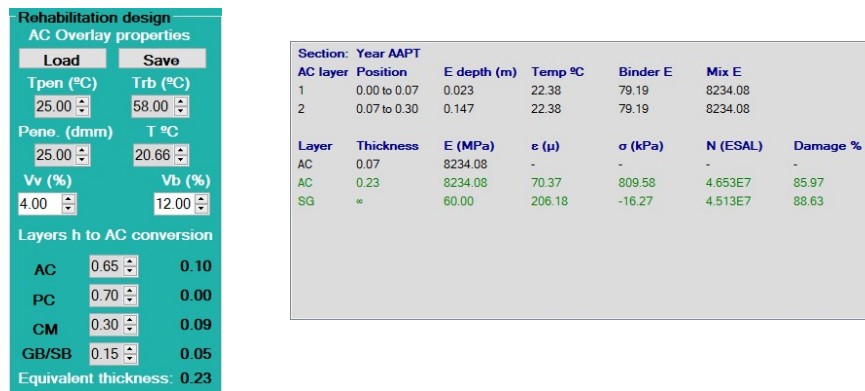


Figure 35 Rehabilitation design example.

4.5.7. Design results

After having completed a design procedure (either in the new or rehabilitation formats), the data that summarizes the information used in the entire process is made available by selecting the “Report” option. By selecting this option, the load data, criteria methods, temperatures, etc., of every pavement section will be displayed in the numerical data section, from where they can be copied to clipboard by using a right mouse button click.

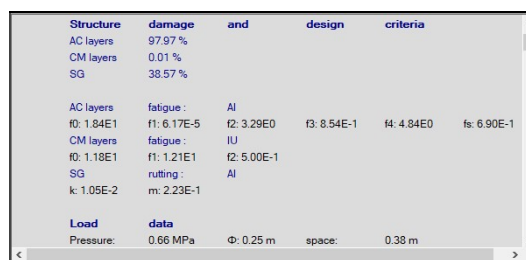


Figure 36 Flexible pavement design report.

4.6. Rigid pavement design

The existing models for designing highway and roads concrete pavements, and in particular the PCA procedure entitled "Thickness Design for Concrete and Street Highway Pavements", result from combining empirical knowledge with the traditional calculation of maximum allowable stresses and deformations, as determined by specifically developed finite elements method models. PCA's design method is divided accordingly to the following six major design parameters:

- Possible existence of transverse joints and dowels/aggregate interlock
- Inclusion of shoulder in the design
- Axle type (Single / Tandem / Tridem) and expected loads/repetitions
- Reaction module (also known as k parameter)
- Concrete slab flexural strength
- Load multiplication factor (depending on the hierarchy of the road)

According to the PCA method, erosion of the slab support surface and concrete fatigue are the ruin criterions to consider. For each pair of load type/expected repetitions, the method determines the maximum allowable repetition; the allowable values are then compared with the expected load repetitions as described in the traffic study.

The procedure consists of an iterative method, in which trial thicknesses are sequentially tested until a satisfactory solution is found.

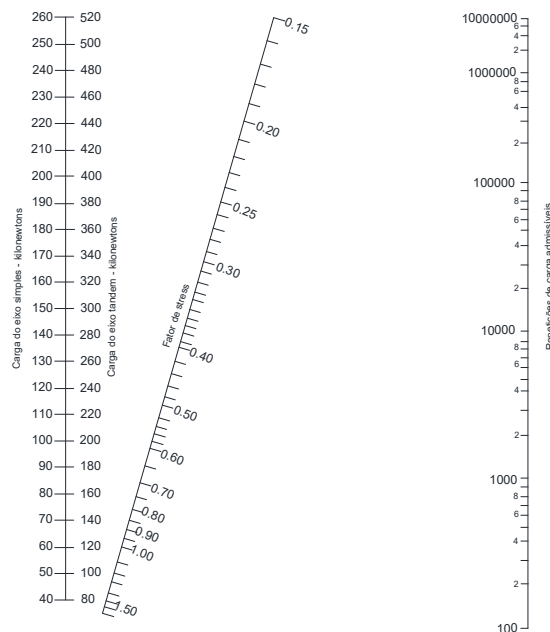
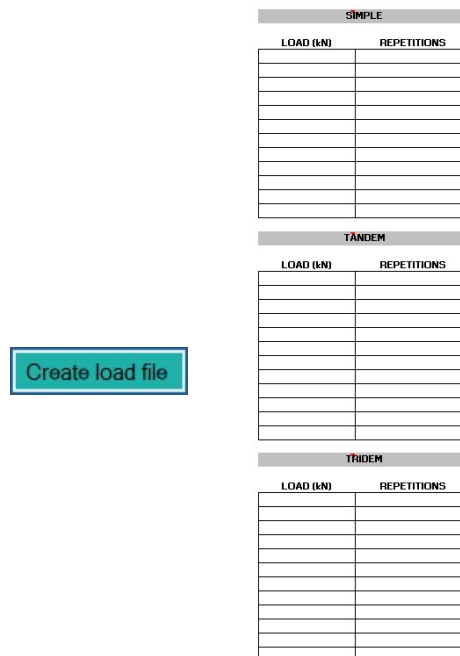


Figure 37 PCA design method.

For DAPS to determine a solution for a cement concrete pavement design, it is necessary to select the "Rigid" tab of the pavement design options. Expected traffic information on which the design is based, is introduced to DAPS via an ".xls" file specially formatted for this purpose. This file is accessed using the "Create load file" button.

It separates traffic in 3 distinct divisions; namely single axle, tandem and tridem axle loads. For each of these categories it is possible to include in the design 12 separate pairs of loads/expected repetitions.

The remaining variables that impact the design procedure (possible existence of transverse joints and dowels or aggregate interlock, possible existence of shoulder, the structures k parameter and load multiplications factor) are selected directly in DAPS window.



The image shows a software interface with a teal button labeled "Create load file" on the left. To the right of the button are three vertically stacked data entry tables. Each table has a header row and 12 data rows. The first table is titled "SIMPLE" and has columns "LOAD (kN)" and "REPETITIONS". The second table is titled "TANDEM" and has the same columns. The third table is titled "TRIDEM" and has the same columns.

| SIMPLE | |
|-----------|-------------|
| LOAD (kN) | REPETITIONS |
| | |
| | |
| | |
| | |
| | |
| | |
| | |
| | |
| | |
| | |
| | |
| | |

| TANDEM | |
|-----------|-------------|
| LOAD (kN) | REPETITIONS |
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| TRIDEM | |
|-----------|-------------|
| LOAD (kN) | REPETITIONS |
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Figure 38 Concrete pavement blank load data file.

Once a traffic load data ".xls" file is opened, DAPS will automatically determine the minimal concrete slab thickness that is required to achieve a satisfactory design. During the design process, DAPS will iteratively add one millimeter to the trial cement concrete slab thickness, until both the concrete fatigue and subgrade erosion criteria are met.

A valid solution is found when both criteria sums of the ratios of maximum allowable repetitions/expected repetitions for each type of load included in the ".xls" file are inferior to 100%. The maximum allowable repetitions are stated in the results (under the "fatigue" and "erosion" columns). The numerical results include a summary of the design settings, and can also be copied to clipboard and transferred to other applications, by right mouse clicking on the numerical data.

| Concrete slab Flexural strength σ <input type="text" value="4"/> MPa | | <input type="button" value="Open load file"/> <input type="button" value="Create load file"/> | | <input type="button" value="Evaluate"/> <input type="text" value="118"/> mm | | <input type="button" value="Automatic design"/> | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
|---|---------|---|----------|---|------------|---|--|---------|---------|----------|---------|--------|---------|--------|--------|-------|-----|-----|--------|--------|-------|--------|-------|-----|------|--------|--------|-------|--------|-------|------|-------|--------|--------|-------|--------|-------|------|-------|-------|--------|-------|--------|-------|------|--------|-------|---------|-------|--------|-------|-------|----------|-------|----------|-------|--------|-------|-------|----------|-------|----------|-------|--------|--------|-----|--------|-------|--------|-------|--------|--------|------|---------|-------|---------|-------|--------|--------|------|----------|-------|---------|-------|--------|--------|------|----------|-------|----------|-------|--------|-------|------|----------|-------|----------|-------|------------|--|--|--|--------|------------|-------|
| Continuous or jointed? <input checked="" type="radio"/> Continuous <input type="radio"/> Jointed (dowels) <input type="radio"/> Jointed (interlock) | | <table border="1"> <thead> <tr> <th>Axle(s)</th> <th>kN x MF</th> <th>Expected</th> <th>Fatigue</th> <th>Fat. %</th> <th>Erosion</th> <th>Ero. %</th> </tr> </thead> <tbody> <tr><td>SIMPLE</td><td>98.00</td><td>130</td><td>303</td><td>42.81%</td><td>115102</td><td>0.11%</td></tr> <tr><td>SIMPLE</td><td>89.00</td><td>260</td><td>1738</td><td>14.95%</td><td>215710</td><td>0.12%</td></tr> <tr><td>SIMPLE</td><td>80.00</td><td>2100</td><td>10482</td><td>20.03%</td><td>427512</td><td>0.49%</td></tr> <tr><td>SIMPLE</td><td>71.00</td><td>5000</td><td>64005</td><td>7.81%</td><td>954791</td><td>0.52%</td></tr> <tr><td>SIMPLE</td><td>62.00</td><td>7400</td><td>531595</td><td>1.39%</td><td>3007583</td><td>0.25%</td></tr> <tr><td>SIMPLE</td><td>53.00</td><td>16300</td><td>∞</td><td>0.00%</td><td>81451277</td><td>0.02%</td></tr> <tr><td>SIMPLE</td><td>42.00</td><td>26900</td><td>∞</td><td>0.00%</td><td>∞</td><td>0.00%</td></tr> <tr><td>TANDEM</td><td>160.00</td><td>550</td><td>117913</td><td>0.47%</td><td>820652</td><td>0.07%</td></tr> <tr><td>TANDEM</td><td>140.00</td><td>9100</td><td>1318827</td><td>0.69%</td><td>2364681</td><td>0.38%</td></tr> <tr><td>TANDEM</td><td>124.00</td><td>9000</td><td>∞</td><td>0.00%</td><td>9566057</td><td>0.09%</td></tr> <tr><td>TANDEM</td><td>106.00</td><td>5100</td><td>∞</td><td>0.00%</td><td>∞</td><td>0.00%</td></tr> <tr><td>TANDEM</td><td>89.00</td><td>7500</td><td>∞</td><td>0.00%</td><td>∞</td><td>0.00%</td></tr> <tr> <td colspan="4">$\Sigma =$</td> <td>88.16%</td> <td>$\Sigma =$</td> <td>2.06%</td> </tr> </tbody> </table> | | | | | | Axle(s) | kN x MF | Expected | Fatigue | Fat. % | Erosion | Ero. % | SIMPLE | 98.00 | 130 | 303 | 42.81% | 115102 | 0.11% | SIMPLE | 89.00 | 260 | 1738 | 14.95% | 215710 | 0.12% | SIMPLE | 80.00 | 2100 | 10482 | 20.03% | 427512 | 0.49% | SIMPLE | 71.00 | 5000 | 64005 | 7.81% | 954791 | 0.52% | SIMPLE | 62.00 | 7400 | 531595 | 1.39% | 3007583 | 0.25% | SIMPLE | 53.00 | 16300 | ∞ | 0.00% | 81451277 | 0.02% | SIMPLE | 42.00 | 26900 | ∞ | 0.00% | ∞ | 0.00% | TANDEM | 160.00 | 550 | 117913 | 0.47% | 820652 | 0.07% | TANDEM | 140.00 | 9100 | 1318827 | 0.69% | 2364681 | 0.38% | TANDEM | 124.00 | 9000 | ∞ | 0.00% | 9566057 | 0.09% | TANDEM | 106.00 | 5100 | ∞ | 0.00% | ∞ | 0.00% | TANDEM | 89.00 | 7500 | ∞ | 0.00% | ∞ | 0.00% | $\Sigma =$ | | | | 88.16% | $\Sigma =$ | 2.06% |
| Axle(s) | kN x MF | Expected | Fatigue | Fat. % | Erosion | Ero. % | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| SIMPLE | 98.00 | 130 | 303 | 42.81% | 115102 | 0.11% | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| SIMPLE | 89.00 | 260 | 1738 | 14.95% | 215710 | 0.12% | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| SIMPLE | 80.00 | 2100 | 10482 | 20.03% | 427512 | 0.49% | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| SIMPLE | 71.00 | 5000 | 64005 | 7.81% | 954791 | 0.52% | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| SIMPLE | 62.00 | 7400 | 531595 | 1.39% | 3007583 | 0.25% | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| SIMPLE | 53.00 | 16300 | ∞ | 0.00% | 81451277 | 0.02% | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| SIMPLE | 42.00 | 26900 | ∞ | 0.00% | ∞ | 0.00% | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| TANDEM | 160.00 | 550 | 117913 | 0.47% | 820652 | 0.07% | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| TANDEM | 140.00 | 9100 | 1318827 | 0.69% | 2364681 | 0.38% | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| TANDEM | 124.00 | 9000 | ∞ | 0.00% | 9566057 | 0.09% | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| TANDEM | 106.00 | 5100 | ∞ | 0.00% | ∞ | 0.00% | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| TANDEM | 89.00 | 7500 | ∞ | 0.00% | ∞ | 0.00% | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| $\Sigma =$ | | | | 88.16% | $\Sigma =$ | 2.06% | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Consider shoulder? <input checked="" type="radio"/> Yes <input type="radio"/> No | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| K Value <input type="button" value="From structure"/> <input type="text" value="80"/> MPa/m | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Type of traffic <input checked="" type="radio"/> Reduced (MF=1.0) <input type="radio"/> Moderate (MF=1.1) <input type="radio"/> Intense (MF=1.2) <input type="radio"/> Exceptional (MF=1.3) | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| | | Slab: 118 mm | | σ : 4.00 MPa | | K = 80.0 MPa/m | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| | | Shoulder: Yes | | Jointed: No | | MF=1.0 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |

Figure 39 Concrete pavement design example.

It is possible to test any other concrete slab thickness intended by the designer, just by entering the desired thickness in the correspondent field and by pressing the "Evaluate" button afterwards. It is also possible to obtain the k parameter of a valid pavement structure that is at that moment defined in DAPS elastic module "Pavement structure" field (4.1) in order to use it directly in the concrete pavement design to be made.

5. BACKCALCULATION MODULE

DAPS is designed to analyze FWD tests that use between five to nine sensors. The sensors distance must be established in sequential order, from D1 at the center of the load, to the furthest sensor Dn. DAPS will allow to backcalculate pavement structures that consist of the subgrade and up to four additional layers. It will also admit an optional bedrock representative layer or to subdivide the subgrade layer. The backcalculation module will be mostly not functional until a raw Falling Weight Deflectometer test file (or multiple files) is loaded.



Figure 40 Backcalculation module window.

5.1. FWD test file loading

To initiate the backanalysis procedure of the data obtained in a Falling Weight Deflectometer test campaign, it will be necessary to load the corresponding raw data file or files; DAPS will open any number of raw data files desired by the user simultaneously. To load the raw data file(s), it is first necessary to select the "Open File(s)" option of the "File" menu. Doing so will prompt a dialog window, in which the user must select the type of raw data files that are to be analyzed. DAPS is prepared to read the following test data formats:

- AASHTO (.ddx)
- ABATECH (.csv)
- CARLBRO (.fwd)
- DYNATEST (.fwd, .f20, .f25)
- JILS (.dat)
- KUAB (.dat)
- PAVETESTING (.csv)

Some example FWD test files are located in the DAPS setup folder. When opening raw test files it is important not just to select the correct file extension, but also the right file format. For example, the KUAB and JILS formats both share the ".dat" extension, but trying to open a JILS data file after selecting the KUAB format will result in error, and vice-versa.

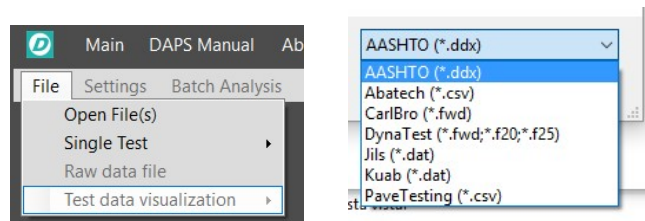


Figure 41 Opening FWD raw data files.

The capacity to load more than one file simultaneously means that it will possible to (for example) backcalculate all of the tests alignments performed side by side over the length of an airport runway in one single take. After loading the desired test data, the Backcalculation module window will be divided in four different major areas.

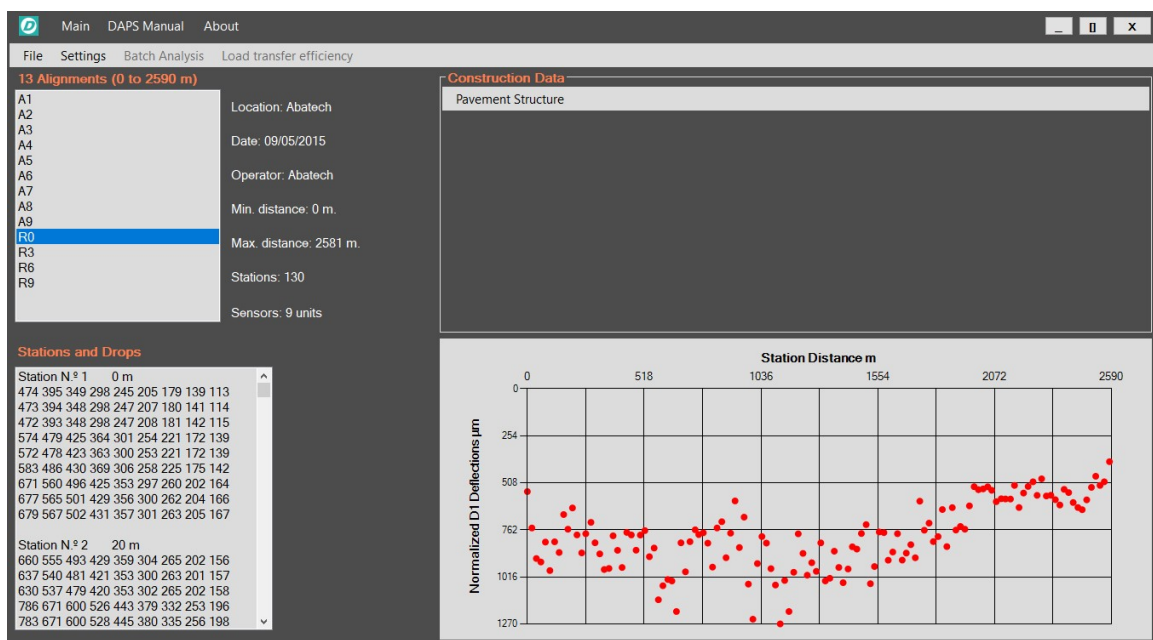


Figure 42 Main backcalculation module window division.

On the top left area, there will be a list of the designation of the loaded alignments, along with some basic information on the selected test line (date, location, number of stations and sensors, etc ...).

| 13 Alignments (0 to 2590 m) | |
|-----------------------------|-----------------------|
| A1 | Location: Abatech |
| A2 | Date: 18/05/2015 |
| A3 | Operator: Abatech |
| A4 | Min. distance: 0 m. |
| A5 | Max. distance: 189 m. |
| A6 | Stations: 21 |
| A7 | Sensors: 9 units |
| A8 | |
| A9 | |
| R0 | |
| R3 | |
| R6 | |
| R9 | |

Figure 43 Loaded alignments list.

The lower left area will contain more information on the Stations and corresponding drops that were performed in that same selected test line.

| Stations and Drops | |
|--------------------|---------------------------------|
| Station N.º 4 | 30 m |
| 436 | 315 266 220 179 151 132 105 89 |
| 429 | 314 265 219 179 150 132 105 90 |
| 430 | 316 266 220 180 151 133 106 90 |
| 533 | 392 329 273 223 187 164 130 111 |
| 530 | 389 327 272 221 187 164 130 110 |
| 532 | 391 329 273 222 188 164 130 111 |
| 628 | 460 390 322 262 221 193 153 130 |
| 629 | 461 389 323 263 222 193 153 130 |
| 632 | 462 390 324 264 222 194 153 130 |
| Station N.º 5 | 40 m |
| 336 | 261 230 197 164 140 123 100 85 |
| 329 | 257 226 194 161 138 122 99 84 |
| 328 | 257 227 194 162 138 122 99 84 |
| 403 | 316 279 239 199 170 149 121 102 |

Figure 44 Station and drop data of the selected test alignment.

The lower right area will contain a graphic with the normalized D1 deflections of the selected alignment. In this graphic, stations with at least one valid drop will be represented by a red circle, and stations without valid drops will be represented by a blue circle and a normalized D1 deflection of value equal to zero.

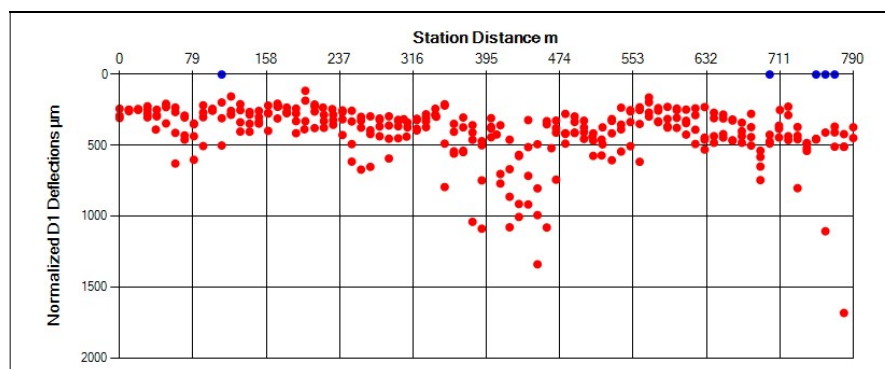


Figure 45 Normalized D1 deflections of the selected test alignment.

5.2. Visualizing the content of raw data files

After the data file or files have been loaded, it is possible to select the "Raw Data File" item of the "File" menu, in order to visualize the original raw data file contents, as produced by the testing equipment. The raw data file that will be exhibited corresponds to that of the currently selected alignment.

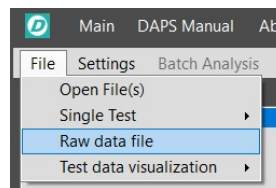


Figure 46 Selection of the Raw Data file.

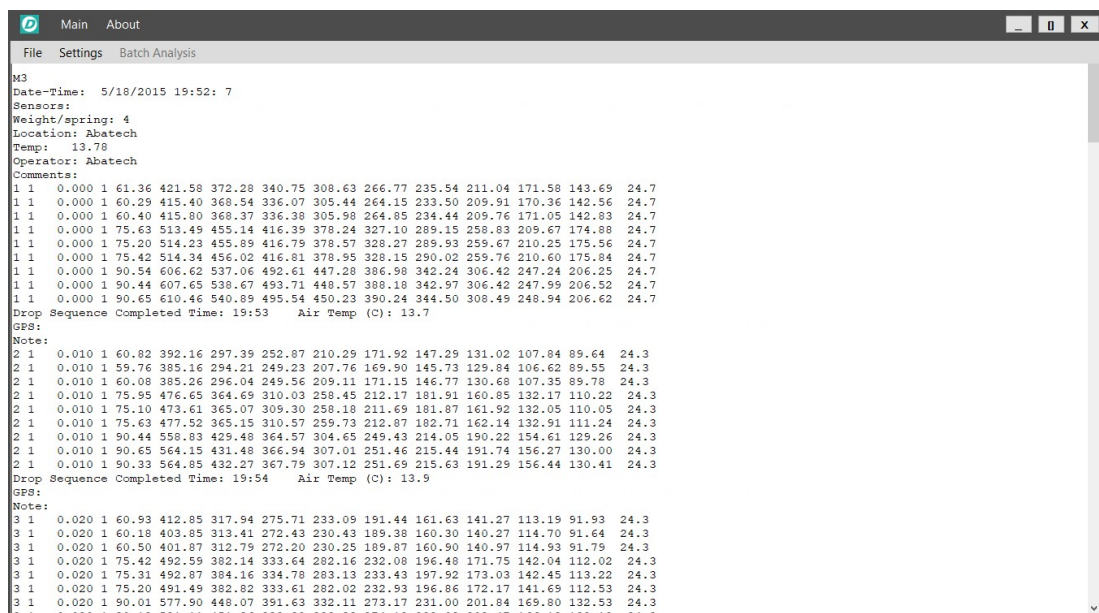


Figure 47 Raw Data window.

To go back to the Backcalculation module main window, it is necessary to click the "Raw data file" item again in order to uncheck it.

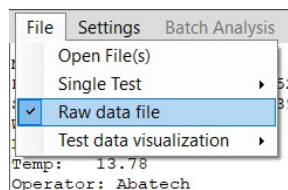


Figure 48 Switch from the raw data view to the main backcalculation window.

5.3. Writing FWD test information to KML files

If the coordinates of the performed tests are listed in the original raw data files, DAPS allows to write their corresponding geospatial data into files of the ".kml" Google® Earth® format. To access the options that relate to FWD tests to KML files conversion, it is necessary to select the menu "Test data visualization" of the "File" options.

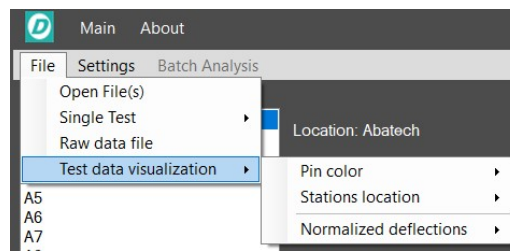


Figure 49 Test data visualization options.

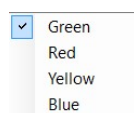
For DAPS to recognize the coordinates that are associated to each test station in the FWD raw files, it is necessary that they are stated in any of the following three different formats:

- 1) Decimal degrees: $DDD.DDDDD^{\circ}$
- 2) Degrees and decimal minutes: $DDD^{\circ} MM.MMM'$
- 3) Degrees, minutes and seconds: $DDD^{\circ} MM' SS.SSS''$

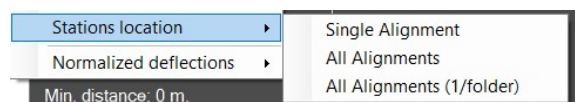
There are two types of information that can be transferred from the raw FWD test files to the DAPS generated KML files:

- **Location and identification of the FWD stations**
- **An comparative assessment of the performance of the pavement and its layers**

Should the user only wish to visualize the geospatial dispersion and location of the FWD test stations, the information that is copied to the KML files will list the coordinates (latitude and longitude) at which the tests were performed and also the corresponding station number and distance. Each station will be represented by an individual pin; pin colors can be defined by the user although the green color is standard and will be automatically selected at the start of each session.



a) Pin color selection



b) File writing

Figure 50 Writing FWD tests geospatial data to file.

By using the "Single Alignment" option of the "Stations location" item, the geospatial data regarding the alignment that is currently selected will be written to the same folder where the test file is located. The last two options will save the coordinates of all loaded alignments, the difference being that the "All Alignments 1/folder" option will place each alignment in a separate folder inside the file. Opening the "kml" extension files that result from using these options will automatically launch Google[®] Earth[®] and allow the visualization of the tests locations.



Figure 51 Visualization of a FWD test alignment.

Should the user wish to visualize information on the pavements performance and layer properties, by comparing normalized deflection data, DAPS enables a simple qualitative evaluation of the pavement by inspecting the following parameters:

- **First sensor** Provides an indication of the total pavement performance
- **(D1-D3)** Provides an indication of the condition of the upper layers
- **Last sensor** Provides an indication of the soil stiffness

By dividing these normalized deflections in five percentile categories and by representing each station on a map accordingly to their calculated interval and color categories, DAPS enables to immediately locate the better and worst areas of the tested pavement. The percentile division and corresponding color assignment is as follows:

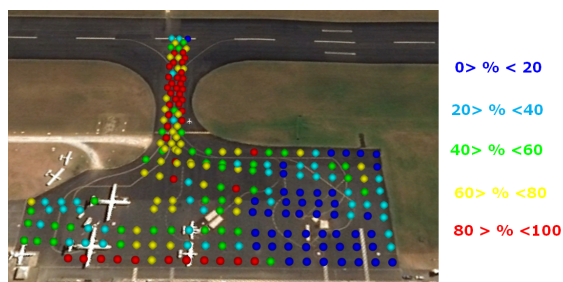
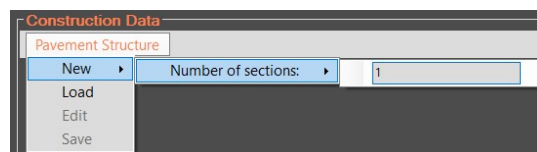


Figure 52 Normalized first sensor deflections for FWD tests of an airport apron and taxiway.

Better performance is represented by cold colors (blue) while worst performance is represented by warm colors (red). It is important to emphasize that this better/worst performance classification is made only considering the universe of tested pavement sections for which DAPS has information; it does not mean that a particular pavement or section passes or fails a certain requirement or specification. It is merely a closed circuit evaluation and comparison of the tested areas.

5.4. Defining the construction data

The top right area of the Backcalculation window is reserved for establishing the construction data that will be used for all the loaded alignments during the batch backanalysis process. To create the construction data that corresponds to the pavement structure throughout the test area, the user has to select the "New" option of the "Pavement Structure" menu, by defining the number of sections necessary. Sections are defined by their start and end distances, number of layers and corresponding mechanical and physical properties. The construction data is the sum of all the possible pavement sections to be considered. The minimum number of pavement sections is 1, the maximum is unlimited.



a) Selection of the number of sections

| Sec. N°: 1/1 | | Layer data and seed values | | | | Modulus cutoff (MPa) | |
|---|-------|----------------------------|-----------|--|---------|----------------------|--|
| Type / Density | E MPa | Poisson | Thickness | | Minimum | Maximum | |
| Start: 0 m | 0 | 0.35 | 0.000 | | 0 | 0 | |
| End: 611.00 | 0 | 0.35 | 0.000 | | 0 | 0 | |
| N° Layers: 4 | 0 | 0.35 | 0.000 | | 0 | 0 | |
| | 0 | 0.35 | 0.000 | | 0 | 0 | |
| Copy to next: <input type="checkbox"/> SubGr 18.0 | 0 | 0.40 | ∞ | | 0 | 0 | |

b) Blank section form

Figure 53 Defining new Construction data.

The DAPS backcalculation module will allow for pavement structures of up to four layers above the subgrade. The material of each layer has to be identified both in designation and density. DAPS offers five different types of materials and pre-defined densities from which the user can make his choice, as follows:

- **CM** Cemented materials 22 kN/m³
- **AC** Asphalt concrete 23 kN/m³
- **PC** Portland cement concrete 24 kN/m³
- **GB** Granular base 21 kN/m³
- **SB** Granular sub-base 20 kN/m³

The subgrade representative layer will be identified as such from the start, and will have a pre-defined density of 18 kN/m³. When the user defines the material of each layer by selecting the correspondent dropdown list, the pre-defined densities will automatically be added to their designated fields, along with pre-defined Poisson ratios. All of the predefined densities and Poisson ratios can be altered by the user; these automatic values are just mere suggestions in order to increase the speed of the process as much as possible.

Figure 54 Automatic density and Poisson ratio definition with layer type selection.

It is advisable not to use the AC and PC designations in layers that do not effectively correspond to these material types given the fact that the characteristics of the layers to which these two particular materials relate will be later used by some of the DAPS backcalculation models.


Pavement sections are defined by introducing the material designation and density, seed values for the moduli, and by defining the thickness of each of the considered layers. Seed moduli and layer thicknesses definition are made in exactly the same manner that was previously described for the layered elastic analysis module.

Empty slots between defined layers will not be accepted, and a layer will only be considered as valid when the fields destined for designation of material type, modulus and thickness display green backgrounds simultaneously. For information on how to obtain the best possible seed module to consider, please refer to the "Single Test" chapter of this manual (5.8).


a) Invalid structure

b) valid structure

Figure 55 Batch backanalysis single section definition.

The end and start distance of the construction data will automatically be assumed as equal to the minimum and maximum distances of the station distances stated in the previously loaded test files, and there will be no need for defining these variables, pavement section definition will be complete after successfully establishing the pavement structure and by pressing the forward/finish button .

5.4.1. Multi-section pavement data

When considering more than one pavement section in the Construction Data, pavement properties definition is made in exactly the same way as previously described for the single section, however it is impossible to automatically define both the start and end distances of each individual section, the latter will require the users input. Each section has to be successfully defined before continuing to the next; advancing to the next section requires pressing the  button which will only be available if the pavement structure is valid and if the start and end distances are also correctly defined. By moving forward to the next section, the end distance of the i section, will automatically become the start distance of the $i+1$ section.

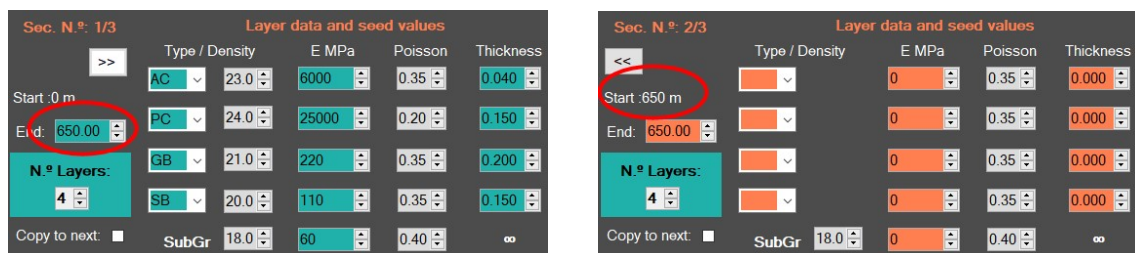


Figure 56 Automatic start distance definition with section advance.

To make the multi-section definition procedure easier and faster, an option denominated as "Copy to next" is available. If this option is selected, when DAPS advances to the next section at the users command, all of the settings defined in the previous section will be automatically copied to the next, except the end distance that has to be manually established. The user can then make changes to the thickness, seed moduli, etc., without having to rebuild the entire pavement section from the start. If the "Copy to next" option is not selected, a blank form will appear instead, as depicted in Figure 56.

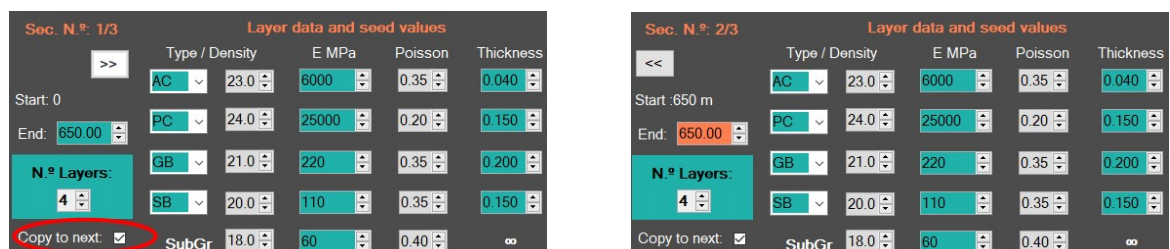


Figure 57 Copying information between pavement sections.

It is possible to go back and forth the considered sections using the << and >> buttons, however, only the forward >> button effectively saves section information. For example to finish the Construction Data definition, it is necessary to press the >> button, while in the last section. For this particular section, the end distance will be automatically defined; the user will only have to complete the pavement layer information to successfully define the section pavement data.

5.4.2. Defining limits to the backcalculated layer moduli

For backcalculation purposes, it will be possible to assign fixed value moduli or even possible moduli interval for each of the considered layers by checking the limits box and by defining minimum and maximum admissible values. For example:

- 1) **Fixed value:** checking the limits box but leaving the minimum and maximum fields with zero value, implies that DAPS will always consider the value that was introduced as seed (=10000 MPa for this specific example) for that particular layer.

The screenshot shows a horizontal bar with several input fields. From left to right: a green field with '10000', a grey field with '0.20', a green field with '0.150', a checked checkbox, a grey field with '0', and another grey field with '0'.

- 2) **Defining a minimum value:** checking the limits box and only defining a minimum value, will not allow DAPS to consider modulus values below the minimum defined (>8000 MPa, for this specific example).

The screenshot shows a horizontal bar with several input fields. From left to right: a green field with '10000', a grey field with '0.20', a green field with '0.150', a checked checkbox, a grey field with '8000', and a grey field with '0'.

- 3) **Defining a maximum value:** checking the limits box and only defining a maximum value, will not allow DAPS to consider modulus values over the maximum defined (<12000 MPa, for this specific example).

The screenshot shows a horizontal bar with several input fields. From left to right: a green field with '10000', a grey field with '0.20', a green field with '0.150', a checked checkbox, a grey field with '0', and a grey field with '12000'.

- 4) **Defining an interval:** by checking the limits box and defining a minimum and maximum values, DAPS will only consider modulus values comprised in the interval between those two values (>8000 and <12000 MPa, for this specific example).

The screenshot shows a horizontal bar with several input fields. From left to right: a green field with '10000', a grey field with '0.20', a green field with '0.150', a checked checkbox, a grey field with '8000', and a grey field with '12000'.

Not checking the limits box at all, will imply that there are no restrictions to the values of the backcalculated moduli. It is possible to impose limitations on the calculated modulus of every layer, including the subgrade.

It is the user's choices to decide which (if any) are the limits that should be used.

5.4.3. Construction data loading, saving and editing

After having defined all of the desired sections, the upper right area of the main window will be occupied by a graphic that summarizes the Construction Data and allows the user to at any time collect some basic information about the layer data that was previously introduced, by moving the dedicated slider control to any particular section of those considered in the total length of the Construction Data. Information on the loaded pavement sections is available at any time by (number and thickness of pavement layers, along with start and end distances of each section), by moving the slider control to the desired distance/section.

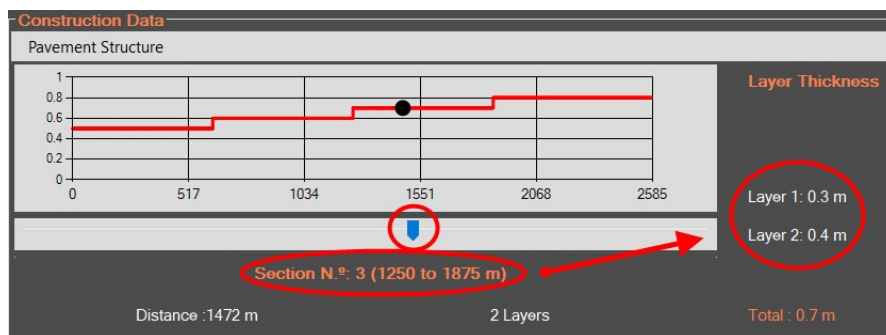


Figure 58 Construction Data summary graphic.

It is possible (but not strictly necessary) to save the Construction Data information to file in order to use it again at a later time, just as it is possible to load an existing Construction Data file at any moment, by using the "Load" and "Save" options that are included in the Pavement Structure menu. It is also possible to perform changes to the existing Construction Data set, by selecting the "Edit" item.

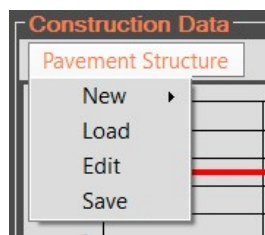


Figure 59 Construction Data file options.

DAPS will assume exactly the same construction data to all of the loaded FWD raw data files. Therefore the batch analysis of multiple raw data files simultaneously is a feature that should only be used when the FWD tests share the same pavement structure data, including start and end distances of possible multiple sections to include in the process.

5.5. Settings

In the backcalculation settings menu, the user will be able to select a variety of parameters that will control the FWD backanalysis process, and that must be defined before initiating the batch calculation.

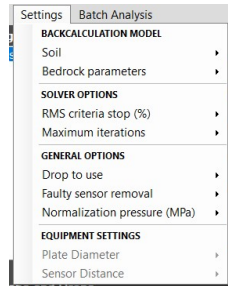


Figure 60 Settings menu.

These options can be described as follows:

5.5.1. Backcalculation model

Backcalculation models are the conceptual basis on which the subgrade non-linearity and presence or absence of bedrock are considered by the backanalysis algorithm. The subgrade can be modeled as being infinite and of constant stiffness in depth, or can be subdivided into a number of sub-layers in order to mimic the soil's nonlinear behavior; the stiffness of each of the subgrade representative layers can then be calculated as stress dependent, or varying linearly as a function of depth. In alternative, it is also possible to assume a stiff bedrock representative layer. The choice of the most appropriate soil model is made based on the available geotechnical data of the test site and the experience of the Engineer that is conducting the backcalculation process.

It is possible to choose between the following models:

- **KHS** Known half-space: There will be no bedrock considered, i.e., the subgrade is considered infinite in depth, and with a constant modulus.
- **CDB** Constant depth to bedrock: A bedrock (of fixed depth and stiffness, as defined by the user), is considered in the analysis.
- **CB/KS** Constant depth to bedrock / known half space: Uses the two previously described models. First considers the CDB model, if a **rms** value lower or equal to the **rms goal** is not achieved by the end of the iterations limit, DAPS automatically switches to the KHS model and tries to find a solution with this model. The final results will display a Y or N notation (Yes or No) to let the user know with which of these two models the optimization algorithm found the best solution.

- **VDB** Variable depth to bedrock: Based on the measured deflections and using the Rhode and Scullion method, the depth to bedrock is a variable that will be determined in each calculated drop. The stiffness of the bedrock is the one defined by the user; the final results will display the calculated depth to bedrock.
- **SDS** Stress dependent subgrade: The subgrade is divided into 4 sub-layers on top of an infinite depth half-space. The stiffness of each sub-layer is determined using the method described by Tam and Brown, based on the pressure applied by the pavement structure in each evaluation point and the stresses transmitted by the FWD load.

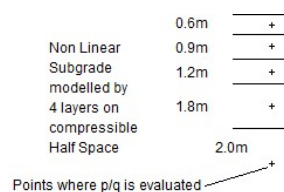


Figure 61 Subgrade subdivisions for the SDS model.

The results will display the ratios between the top subgrade layer and those of the remaining subgrade layers.

- **GIB** Gibson soil model: Similar to the SDS model in terms of subgrade subdivision, but the change in stiffness of the considered sub-layers will be linear (function of the depth that is being considered). The stiffness at a depth z is equal to $E_{sg} + z \times E_{sg} \times \text{ratio}$. The final results will display the initial subgrade stiffness and the percentage of stiffness increase with depth (ex: 101.35 MPa and 20% / meter).

5.5.2. Bedrock parameters

Using these options the user can define the stiffness of the bedrock that is to be considered, and also the depth at which the bedrock stratum will be located. This information will only be used by the backcalculation models that consider a bedrock representative layer. The subgrade depth parameter defines the distance between the upper face of the subgrade and the upper face of the bedrock.

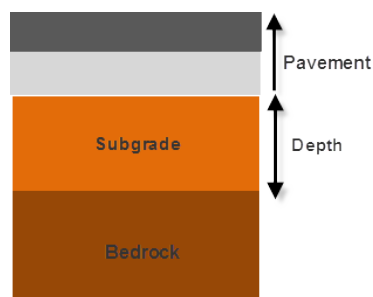


Figure 62 Bedrock depth.

5.5.3. Solver options

DAPS uses an iterative numerical optimization algorithm in order to find a suitable match between the measured and calculated deflection bowls. In all iterations a set of different stiffness's are assigned to every layer, in order to obtain the combination that presents a better fit between the calculated and measured deflections for all sensor positions. The best set of moduli of the previous iteration is used as base for the next iteration, thus resulting in a gradual approximation to the actual layer stiffness's of the tested pavement. The user can select the number of maximum iterations for each drop (50 or 100). The rms criteria stop (value at which DAPS terminates the iterative process) can also be selected by the user in the interval that is comprised by the 2% and 8% limits.

5.5.4. General options

- **Drop to use:** It is possible to select the drop that is to be used by DAPS during the batch backcalculation process of each station; either the last drop can be selected or DAPS can determine the drop that will lead to a best fit out of all of those performed in each particular station. This option will only lead to effective changes in stations for which more than a single drop was executed.
- **Faulty sensor removal:** The sensor removal option will be helpful in cases where one of the used sensors is providing erroneous readings due to equipment malfunction. By selecting this option from the settings menus, a list of the used sensors will become visible, stating the number and radii of each sensor. To remove the desired sensor it is necessary to select it from this list, action that will result in the immediate removal of the chosen sensor and associate deflection reading from all drops. In situations where more than one test file has been loaded, this option will only be available if all tests were performed using equal sensor numbers.
- **Normalization pressure:** The drops that are executed throughout the FWD test campaign will have varying forces; in order to compare drops directly it is necessary to consider a standard normalization pressure. The resulting normalized deflections will correspond to the measured deflections multiplied by the ratio between the normalization pressure and the actual test pressure. Using this option, the user can select the normalization pressure that is to be considered by DAPS. 1 MPa is the default.

5.5.5. Equipment settings

The last two options of the settings menu (plate diameter and sensor spacing) will only become available should the FWD test file not contain this information, in which case it will be necessary to define these parameters after the test file or files are loaded. If this particular information is not listed in the raw data files, the user will have to define them.

- **Plate diameter:** There are two possible options in regard to the test plate diameter, either the 0.30 meter plate or the 0.45 meter plate.

| | |
|-----------------|--------|
| Plate Diameter | 0.30 m |
| Sensor Distance | 0.45 m |

Figure 63 Test plate diameter selection.

- **Sensor distances:** As far as establishing sensor distances is concerned, by selecting the "New" option, sensor definition related choices will become visible in order to allow the user to select the sensor distances that are to be considered. In this window, after having successfully defined the sensor distances, pressing the "Done" button will make DAPS assume the introduced values as the sensor distances that will later be used in all the backanalysis procedures. Selecting the "Return" button will close this window and make no changes to the backanalysis sensor distance parameters.

| | |
|-----------------|--------|
| Sensor Distance | Define |
| | Load |
| | Save |

a) Sensor definition selection.

| D1 | D2 | D3 | D4 | D5 | D6 | D7 | D8 | D9 |
|-------|-------|-------|-------|-------|-------|-------|-------|-------|
| 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |

Return

b) Blank sensor definition form.

| D1 | D2 | D3 | D4 | D5 | D6 | D7 | D8 | D9 |
|-------|-------|-------|-------|-------|-------|-------|-------|-------|
| 0.000 | 0.200 | 0.300 | 0.450 | 0.600 | 0.750 | 0.900 | 1.200 | 1.500 |

Done Return

c) Complete sensor definition form.

Figure 64 Sensor definition process.

After successful sensor definition, it will be possible to save this specific information to file in order to use it at a later time in situations of similar sensor number and spacing, by using the "Save" option of the "Sensors Distance" menu. These files can also be loaded at any time using the "Load" option, action that will automatically define and update the sensor distance information. When loading a sensor file, DAPS will only accept the data in it contained if the stated number of sensors is equal to the number of sensors that were used for collecting the information stated in the test files.

5.6. Individual drop backcalculation

When all the relevant data for the backcalculation process has been introduced to DAPS (test file(s), pavement construction information, and also sensor distance and test plate diameter if not specifically stated in the test files), performing a batch analysis of all the loaded FWD tests becomes possible, and the "Batch Analysis" menu becomes enabled, thus allowing the user to access its specific features and functionalities.

At this point, selecting any particular drop will replace the selected alignment normalized D1 deflections with graphic and numerical information that will depict the normalized and measured deflections of that same selected drop. Additional information about the selected station and drop, such as date, time and station distance among others, will also be presented. If the selected drop is a valid one, DAPS will permit to perform the corresponding individual backcalculation procedure.

An invalid drop will be one in which the measured deflection of sensor at position $n+1$ is higher than that of the measured deflection of sensor at position n , or that in which any sensor displays a measured deflection equal to zero. These drops will not be considered for analysis in any of the DAPS different features. Stations that only possess invalid drops will be skipped during the batch backanalysis procedure.

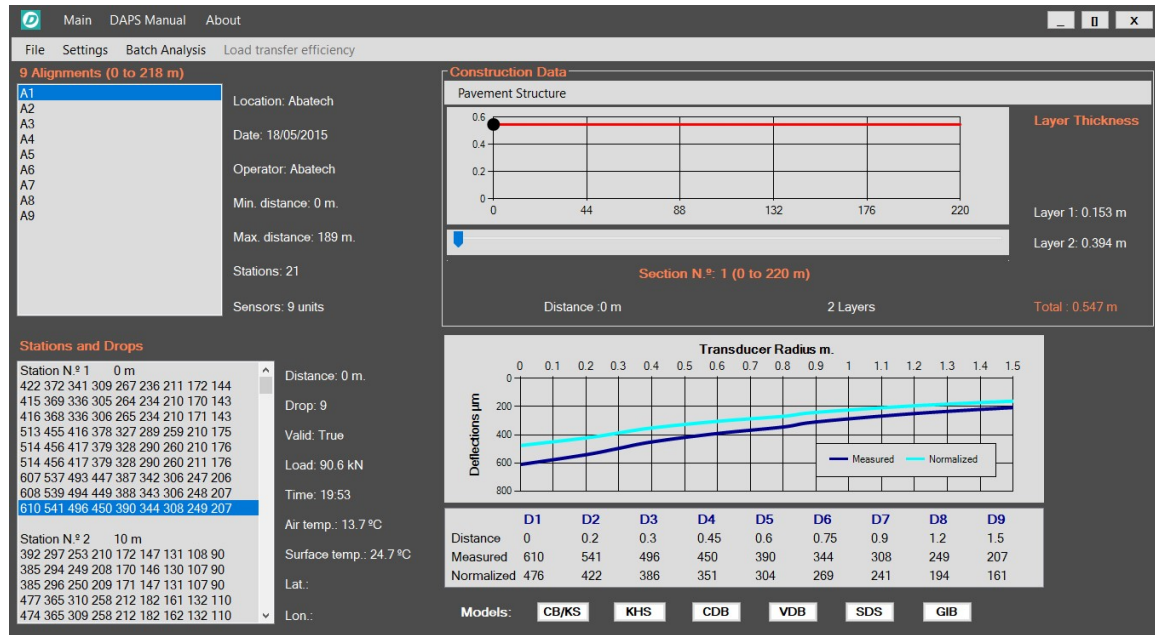


Figure 65 Specific drop selection and individual backcalculation options.

The backcalculation procedure of the selected drop, will assume the construction data that was previously defined by the user; based on the station distance, DAPS will automatically retrieve the corresponding pavement structure and layer properties and assume that particular information as basis for the backanalysis process. All the previously described models can be used, just by selecting their corresponding button. After the process is complete, the window will be updated with the obtained results, including a comparison between the normalized and calculated deflection bowls, and also the layer moduli that correspond to the solution that was calculated by the optimization algorithm. The single drop backcalculation feature can be used any number of times desired, which enables a quick and concise comparison between the results of each specific model, and thus allow adjustment and selection of the best soil model to use in the batch analysis process.

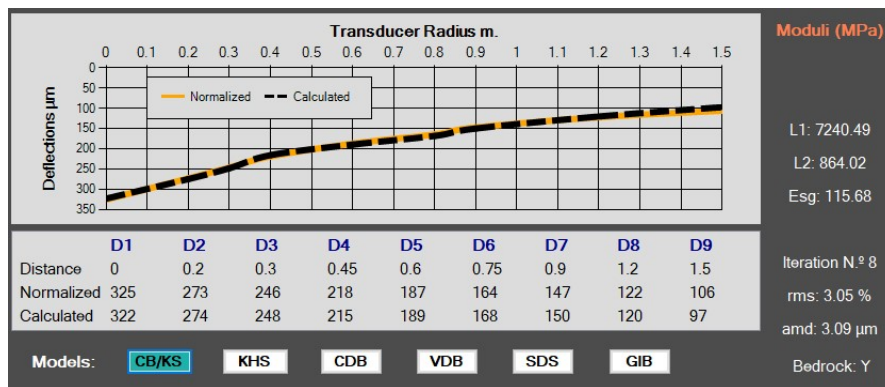


Figure 66 Single drop backcalculation results.

5.7. Batch Analysis

Besides the determination of the layers moduli based on the information collected during the FWD tests, the batch analysis option offers two more additional features in order to provide further information on the tested pavements, namely the Bells asphalt mixture modulus temperature correction and the determination of critical strains.

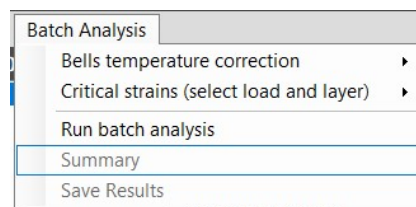


Figure 67 Batch analysis options.

These two options must be selected and appropriately configured by the user before the batch analysis process is initiated.

5.7.1. Bells temperature asphalt modulus correction

The modulus of an asphalt mixture is highly variable and depending on the temperature to which it is exposed to. Therefore, the modulus of a layer of this material is linked to the climatic conditions (temperature and solar radiation) of the location where the pavement in which it was applied is in service, and displays large variations on both yearly and daily basis. The modulus of an asphalt layer obtained directly by backcalculating an FWD test will only be valid for the exact moment at which it was performed. The Bells correction methodology takes in account climatic conditions in order to convert the asphalt layer moduli that result directly from the backanalysis process, to a specific temperature that is considered to be adequately representative of that specific location. In order to perform the Bells correction, it is necessary to know the latitude of the site (stated in the raw data files), as well as the previous day average temperature, the reference temperature (temperature for which the asphalt layer modulus is to be converted to) and the depth for which the correction should be calculated (usually assumed as one third the thickness of the layer). To enable the Bells correction procedure, the user has to check the corresponding option in the "Batch Analysis" menu and then define the previously stated parameters.

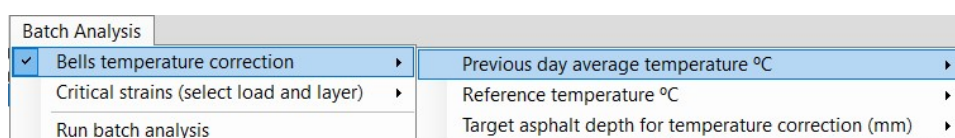


Figure 68 Bells asphalt modulus temperature correction.

After the batch analysis process is complete and if the Bells correction has been enabled, the results will list the asphalt temperature adjustment factor (ATAF) for each station. The asphalt layer modulus must be multiplied by the ATAF factor in order to transform the back analysis calculated moduli to the reference temperature converted ones.

5.7.2. Critical strains determination

DAPS allows to calculate the critical strains (vertical at the top face of the subgrade and horizontal at the lower face of an AC or CM layer) for the layer moduli that result from each stations back analysis. The loads that are available to perform this action are the same that are available in the Elastic analysis module, as described in 4.2. The user must enable this option and then select the load and layer for determination of the horizontal critical strain (layers are numbered from top to bottom). Both critical strains μ_v and μ_h will be made available in the final results file.

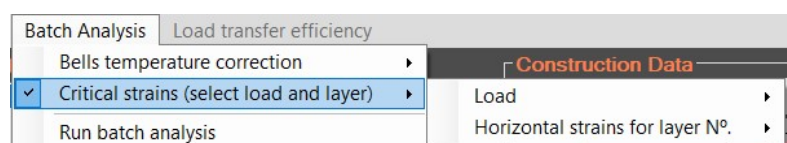


Figure 69 Critical strains.

5.7.3. Layer moduli determination

After having defined the possible inclusion of the Bells correction and critical strains determination, the batch backanalysis process of all FWD test alignments is initiated by selecting the "Run batch analysis" option. It is possible to follow the progress of this operation not only because the Test Alignment that is being analyzed at that moment will be highlighted, but also because the stations for which DAPS has already calculated the correspondent layer moduli variables will be signaled by a green circle instead of a red one.

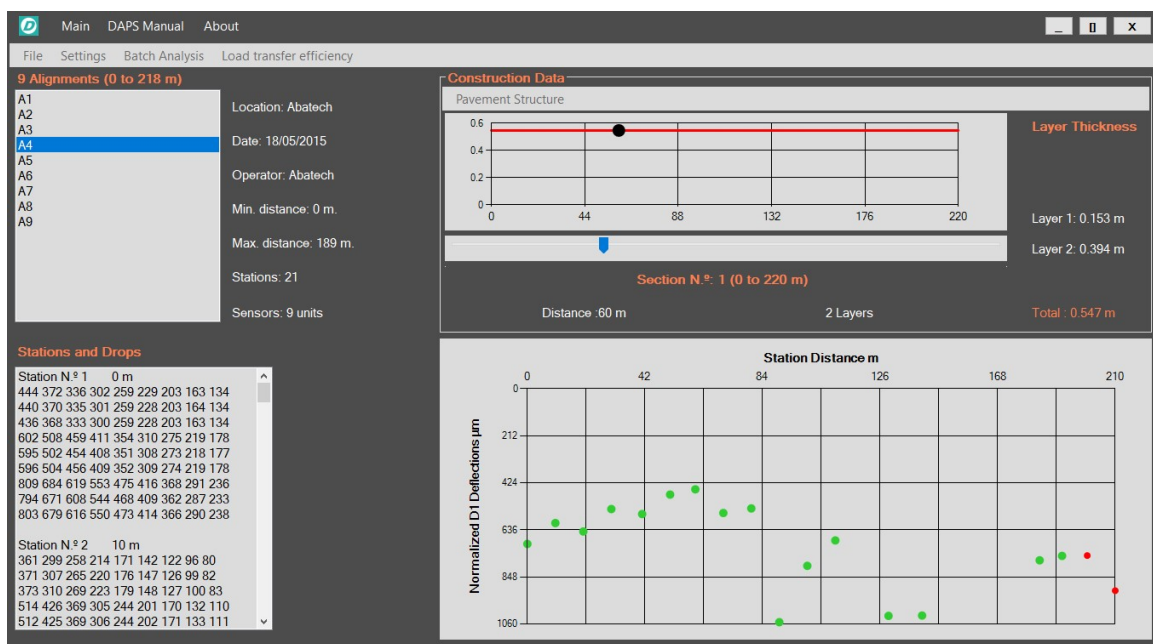
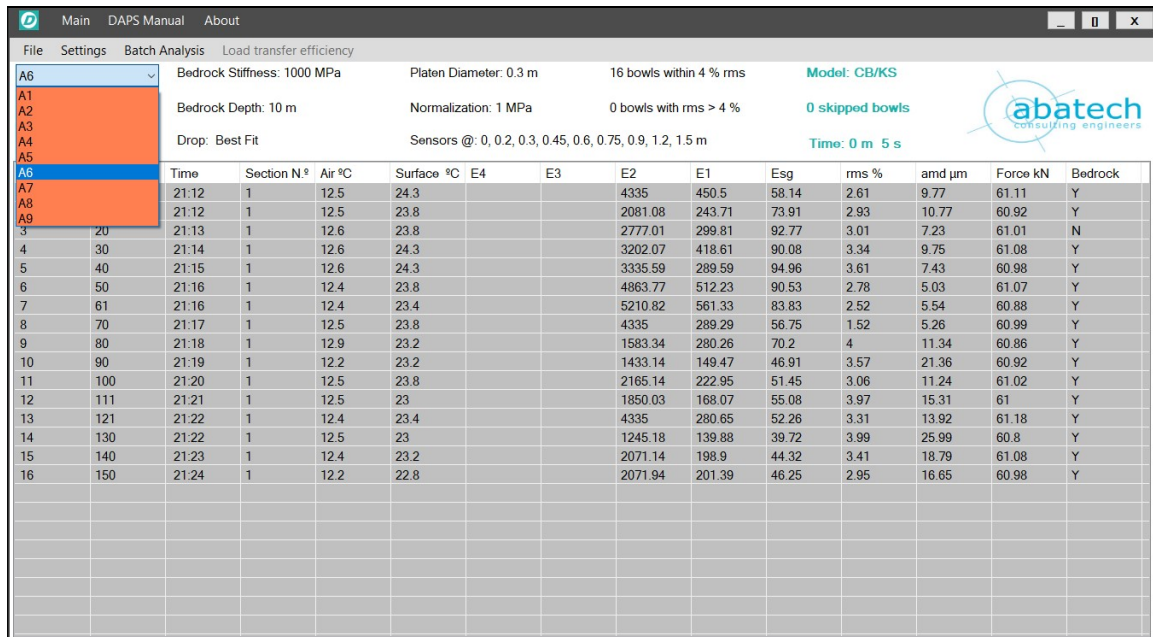


Figure 70 Batch analysis process evolution.

When the backcalculation process is complete, the main window will switch automatically to the results summary view. On the top left corner of this window is located a drop down list that contains the designation of the loaded alignments. By selecting any alignment from this list, the summary table will automatically be updated with the corresponding results. This information will include not only the calculated layer moduli, but also the final **rms** (root mean square) and the **amd** (absolute mean deviation) obtained for each station layer moduli solution.

The Bedrock column will indicate the relevant bedrock and subgrade modeling parameters accordingly to the model that was selected by the user to conduct the backcalculation process.



| | Time | Section N | Air °C | Surface °C | E4 | E3 | E2 | E1 | Esg | rms % | amd µm | Force kN | Bedrock |
|----|-------|-----------|--------|------------|----|----|---------|--------|-------|-------|--------|----------|---------|
| 1 | 21:12 | 1 | 12.5 | 24.3 | | | 4335 | 450.5 | 58.14 | 2.61 | 9.77 | 61.11 | Y |
| 2 | 21:12 | 1 | 12.5 | 23.8 | | | 2081.08 | 243.71 | 73.91 | 2.93 | 10.77 | 60.92 | Y |
| 3 | 21:13 | 1 | 12.6 | 23.8 | | | 2777.01 | 299.81 | 92.77 | 3.01 | 7.23 | 61.01 | N |
| 4 | 21:14 | 1 | 12.6 | 24.3 | | | 3202.07 | 418.61 | 90.08 | 3.34 | 9.75 | 61.08 | Y |
| 5 | 21:15 | 1 | 12.6 | 24.3 | | | 3335.59 | 289.59 | 94.96 | 3.61 | 7.43 | 60.98 | Y |
| 6 | 21:16 | 1 | 12.4 | 23.8 | | | 4863.77 | 512.23 | 90.53 | 2.78 | 5.03 | 61.07 | Y |
| 7 | 21:16 | 1 | 12.4 | 23.4 | | | 5210.82 | 561.33 | 83.83 | 2.52 | 5.54 | 60.88 | Y |
| 8 | 21:17 | 1 | 12.5 | 23.8 | | | 4335 | 289.29 | 56.75 | 1.52 | 5.26 | 60.99 | Y |
| 9 | 21:18 | 1 | 12.9 | 23.2 | | | 1583.34 | 280.26 | 70.2 | 4 | 11.34 | 60.86 | Y |
| 10 | 21:19 | 1 | 12.2 | 23.2 | | | 1433.14 | 149.47 | 46.91 | 3.57 | 21.36 | 60.92 | Y |
| 11 | 21:20 | 1 | 12.5 | 23.8 | | | 2165.14 | 222.95 | 51.45 | 3.06 | 11.24 | 61.02 | Y |
| 12 | 21:21 | 1 | 12.5 | 23 | | | 1850.03 | 168.07 | 55.08 | 3.97 | 15.31 | 61 | Y |
| 13 | 21:22 | 1 | 12.4 | 23.4 | | | 4335 | 280.65 | 52.26 | 3.31 | 13.92 | 61.18 | Y |
| 14 | 21:22 | 1 | 12.5 | 23 | | | 1245.18 | 139.88 | 39.72 | 3.99 | 25.99 | 60.8 | Y |
| 15 | 21:23 | 1 | 12.4 | 23.2 | | | 2071.14 | 198.9 | 44.32 | 3.41 | 18.79 | 61.08 | Y |
| 16 | 21:24 | 1 | 12.2 | 22.8 | | | 2071.94 | 201.39 | 46.25 | 2.95 | 16.65 | 60.98 | Y |

Figure 71 Batch analysis results window.

The parameters stated in the bedrock column will have the following format (depending on the selected soil model):

KHS Known half-space: N (No – bedrock is not considered)

CDB Constant depth to bedrock: Y (Yes – a user defined bedrock is modeled)

CB/KS Constant depth to bedrock / known half space: Y/N (Bedrock was admitted yes or no, depending on the model with which the best solution was found)

VDB Variable depth to bedrock: @ x.x (indicates the calculated depth to bedrock in meters).

SDS Stress dependent subgrade: Esg, r1, r2, r3, r4 (indicates the subgrade stiffness and the corresponding ratio's in regard to each subgrade sublayer. Example: 58.36 MPa, 1.2, 1.6, 1.85, 2.4 is the same as Esg= 58.36; Esg1 = 58.36 x 1.2 , Esg2 = 58.36 x 1.6, Esg3 = 58.36 x 1.85, Esg4 = 58.36 x 2.4)

GIB Gibson soil model: Esg, x.x % (indicates the subgrade stiffness and the ratio of added stiffness with each meter in depth. Example: 101.35 MPa and 25% implies that at a depth of 2 meters the subgrade stiffness will be of 101.35 + 2 x 101.35 x 25%)

5.7.4. Saving the backcalculation results to file

Using the "Save Results" option of the "Batch Backanalysis" menu, will allow saving to an ".xls" file the backcalculation results. A separate worksheet will be considered for every loaded alignment.

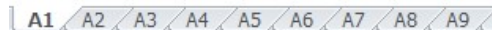


Figure 72 Alignment separation in the results file.

The data that consists of this file will have added information in regard to the one that is exhibited in the results summary table. The "Δ1" titled column will contain the D1 - D3 normalized deflections. The "Δ2" titled column will contain the D1 - Dn (Dn = last sensor) normalized deflections. The results file will also list the normalized deflections for all sensors.

A1 Bedrock Stiffness: 1000 MPa Platen Diameter: 0.3 m 21 bowls within 4% rms Model: CB/KS
 Location: Abatech Bedrock Depth: 10 m Normalization: 1 MPa 0 bowls with rms > 4% 0 skipped bowls
 Date: 18/05/2015 Drop: Best Fit Sensors @: 0, 0.2, 0.3, 0.45, 0.6, 0.75, 0.9, 1.2, 1.5 m



| Station N.º | Chainage | Time | Section | Air °C | Surface °C | E4 | E3 | E2 | E1 | Esg | rms % | amd µm | Force | Bedrock | Δ1 | Δ2 | D1 |
|-------------|----------|-------|---------|--------|------------|----|----|---------|--------|--------|-------|--------|-------|---------|-----|-----|-----|
| 1 | 0 | 19:53 | 1 | 13.7 | 24.7 | | | 5388.2 | 531.06 | 72.31 | 3.32 | 8.17 | 75.55 | Y | 92 | 322 | 488 |
| 2 | 10 | 19:54 | 1 | 13.9 | 24.3 | | | 2454.16 | 591.95 | 120.88 | 3.92 | 4.21 | 75.42 | Y | 159 | 348 | 453 |
| 3 | 20 | 19:55 | 1 | 13.8 | 24.3 | | | 4692.69 | 520.53 | 106.58 | 3.98 | 7.92 | 75.33 | Y | 152 | 363 | 470 |
| 4 | 30 | 19:56 | 1 | 13.9 | 24.3 | | | 2421.12 | 478.08 | 119.95 | 3.96 | 6.02 | 75.64 | Y | 193 | 399 | 504 |
| 5 | 40 | 19:57 | 1 | 13.8 | 24.3 | | | 5463.9 | 638.87 | 130.29 | 3.86 | 5.2 | 76.22 | Y | 117 | 283 | 380 |
| 6 | 50 | 19:58 | 1 | 14.2 | 22.8 | | | 4519.58 | 527 | 137.37 | 3.82 | 6.4 | 76.84 | N | 139 | 322 | 428 |

a) Layer moduli and station identification

| ATAF | Bedrock | Δ1 | Δ2 | D1 | D2 | D3 | D4 | D5 | D6 | D7 | D8 | D9 | Horizontal strain µε | Subgrade strain µε |
|-------|---------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|----------------------|--------------------|
| 1.379 | Y | 91 | 316 | 480 | 425 | 389 | 354 | 306 | 271 | 242 | 196 | 164 | 123.39 | 324.84 |
| 1.36 | N | 156 | 343 | 446 | 341 | 290 | 242 | 198 | 170 | 151 | 124 | 103 | 138.73 | 254.8 |
| 1.36 | Y | 150 | 358 | 463 | 359 | 313 | 265 | 218 | 185 | 161 | 133 | 105 | 123.53 | 270.75 |
| 1.36 | Y | 190 | 393 | 496 | 363 | 306 | 254 | 207 | 174 | 152 | 121 | 103 | 159.18 | 294.54 |
| 1.36 | Y | 116 | 279 | 374 | 293 | 258 | 222 | 184 | 157 | 138 | 112 | 95 | 105.38 | 227.15 |
| 1.292 | N | 137 | 316 | 421 | 327 | 284 | 241 | 196 | 166 | 146 | 120 | 105 | 133.69 | 251.24 |

b) ATAF value, normalized deflections and critical strains

Figure 73 Batch backanalysis results file.

To return to the backcalculation module, it is required to uncheck the "Summary" option of the "Backanalysis" menu.

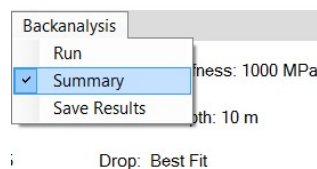


Figure 74 Switch from the summary view to the backcalculation main window.

5.8. Single test window

In order to further experiment with the backcalculation parameters and process, DAPS offers the possibility of launching a separate window, namely the "Single Test" window. This option is available in the "File" menu.

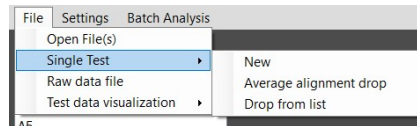


Figure 75 Single test window launch.

The "Single Test" window allows the user to experiment with any possible FWD test configurations (Pavement Structure, sensor distance and deflections, backcalculation settings, etc...), and to simulate the backanalysis of any particular drop configuration.

This separate window will replicate all of DAPS features and functionalities, but will be directed to a particular drop at a time. The principal difference between the "Single Test" window and the single drop analysis available in the backcalculation main window is that the "Single Test" window will allow to make changes to the measured deflections, applied test force, etc ..., thus allowing the user to freely experiment with all possible parameters. It will also be possible to try and manually find the set of layer moduli that will fit a particular measured bowl, or to let DAPS automatically determine these variables. There are three distinct possibilities to launching a Single Test window, as follows:

5.8.1. New single test

The new single test will consist of a completely blank form.

 A screenshot of the 'Single test' window in DAPS 2.0. The window is titled 'Single test' and contains several sections for data entry:

- Pavement Structure:** Includes a 'Layers' dropdown set to '4'. Below it is a table with columns: Type, Density, E (MPa), Poisson, m, Min., and Max. The first four rows are for layers, and the last row is for 'SubGr' (Subgrade) with a density of 18.0 and Poisson's ratio of 0.40.
- Modulus Limits:** A section for setting minimum and maximum modulus values.
- Backcalculation model:** Includes radio buttons for 'CB/KS', 'KHS', 'CDB', 'VDB', 'SDS', and 'GIB'. The 'RMS criteria' is set to 4.0 %.
- Bedrock settings:** Includes fields for 'Depth' (10.00 m) and 'Stiffness' (1000 MPa).
- Load:** Includes fields for 'Force' (0.000 kN) and 'Pressure' (0.000 MPa).
- Iterations:** Includes radio buttons for '50' and '100' iterations.
- Normalization:** Includes a field for '1.00 MPa'.
- Plate Diameter:** Includes radio buttons for '0.30 m' and '0.45 m'.
- Sensors:** Includes a field for '7 units'.
- Distance and Deflection Data:** A table with columns for distances D1 through D7. Rows include 'Distance (m)', 'Measured (µm)', 'Normalized (µm)', 'Calculated (µm)', and 'Deviation (µm)'. All values are currently 0.00.
- Buttons and Mode:** A 'Load sensor file' button and a 'Mode' selector with 'auto' and 'manual' options.

Figure 76 New single test form.

All the possible backcalculation parameters will have to be defined by the user, including the sensor number and spacing, as well as the corresponding test deflections. Other settings that must be defined are the force/pressure of the drop, the normalization pressure and the test plate diameter (some of these settings will already be pre-defined with standard values, but can be altered). All of the DAPS included backcalculation models are available in the Single Test window. After having defined all of the variables and settings, it is possible to perform an automatic backcalculation procedure, or to try to manually determine which are the layer moduli that correspond to the drop and test settings in question by pressing the "Run" button. The "Run" button only becomes visible after a valid drop has been correctly defined (pavement structure + sensor distance + measured deflections + applied force). At this point, a graphic with the normalized deflections will also be presented. Layer seed values are defined as previously demonstrated for the single section construction data case.

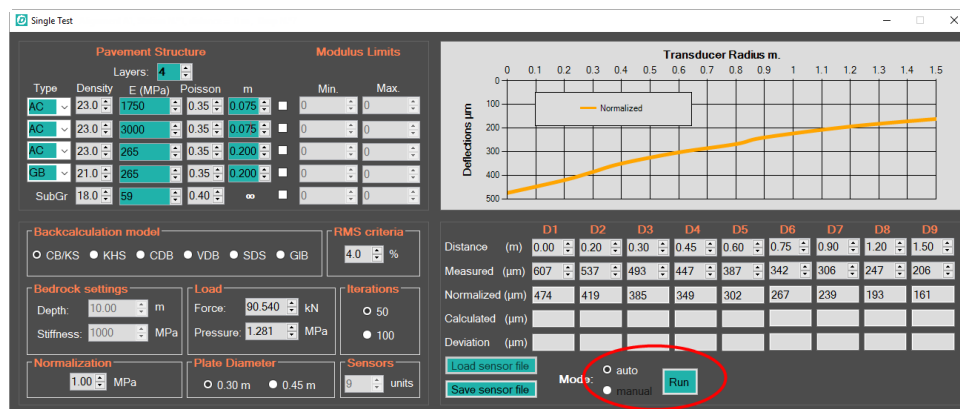


Figure 77 Single test window ready to begin the backanalysis procedure.

If the automatic option is selected, pressing the "Run" button will initiate the backanalysis algorithm, at the end of which, the initial seed moduli will be replaced with the deformability modulus values that were calculated in order to match the normalized deflection bowl.

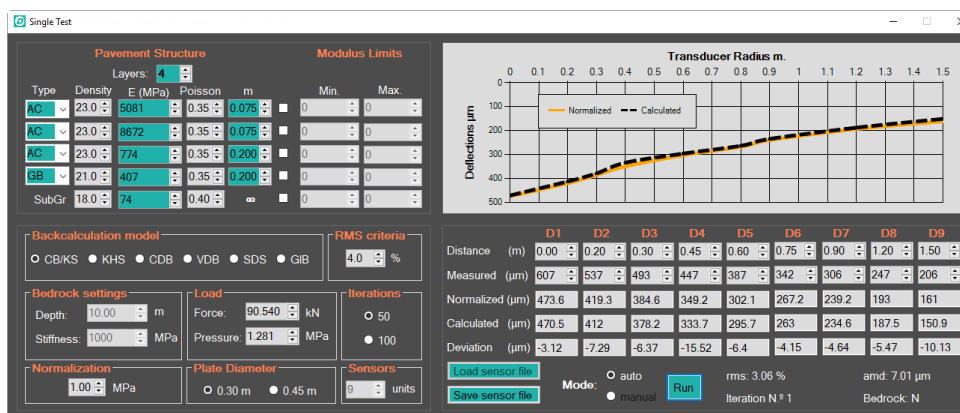


Figure 78 Calculated layer moduli.

After completion of the automated backanalysis algorithm, the deflection chart will also be updated in order to draw the calculated deflection bowl as well as the normalized deflections bowl. Simultaneously the calculated deflections will be displayed, along with the corresponding deviation to the normalized deflections, as well as the number of performed iterations and the final **rms** and absolute mean deviation values obtained.

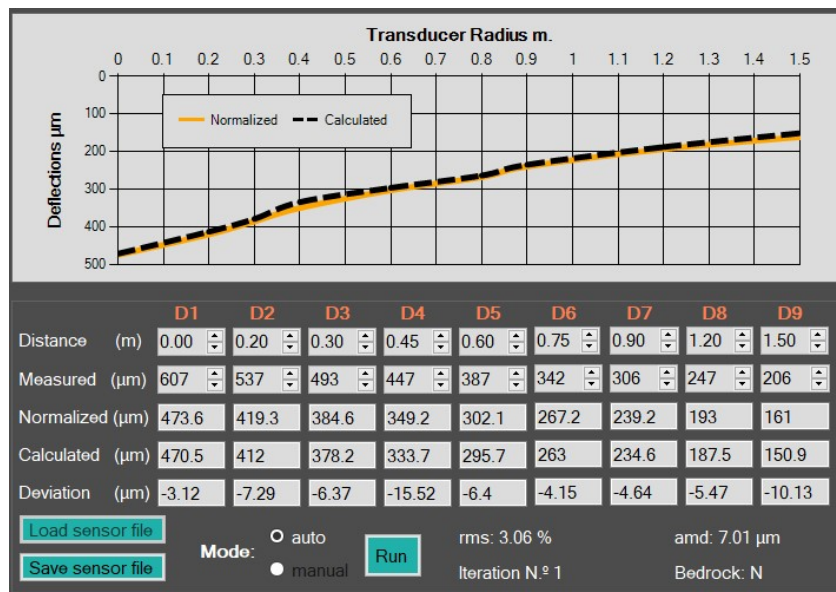


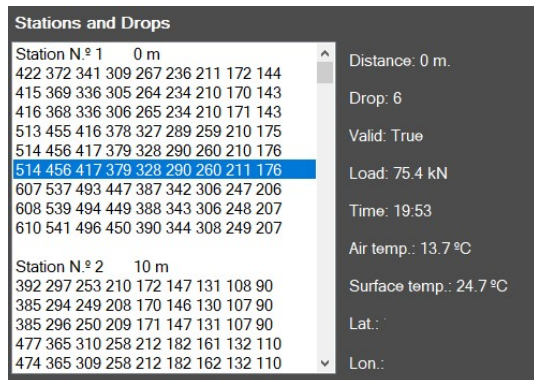
Figure 79 Calculated deflection bowl graphic and numerical data.

Should the manual option be selected, pressing the “Run” button will make DAPS compare the normalized test deflections with those that result from using the seed moduli selected by the user, display the corresponding rms and amd values and draw the calculated deflection bowl, but no other additional action will be performed. To make it easier and faster to work with the Single Test window, sensor distances can be saved to file and loaded posteriorly (by using the save/load sensor file buttons). These sensor data files are identical to those that were previously described in the batch backanalysis settings options, and can be shared between the single test window and the main backcalculation module window.

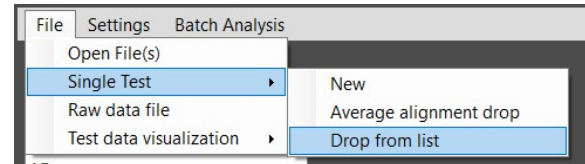
5.8.2. Drop from list single test

Using the “Drop from list” option implies launching a single test window in which all of the variables will coincide with the selected drop in the backcalculation main module.

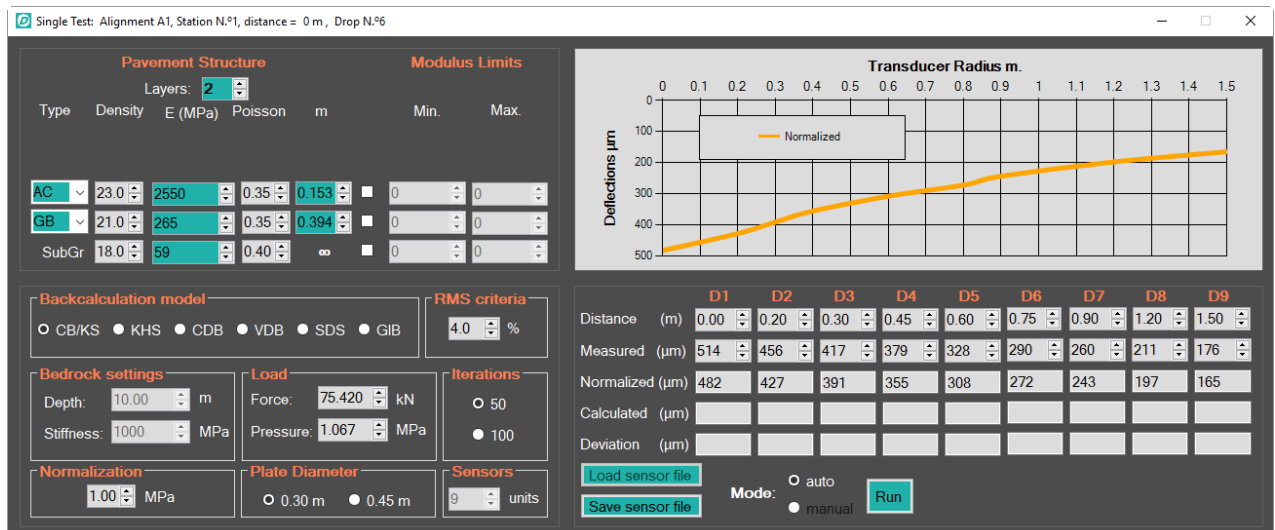
The pavement structure and seed moduli will also be automatically retrieved from the construction data, based on the selected station distance. The single test window that will result from this action will automatically identify the alignment, station and drop from which its data derives.



a) Drop selection



b) "Drop from list" single test launch



c) Resulting single test window

Figure 80 Single test from selected drop.

The single test window, and more specifically the "From List" option can be used to determine the set of layer moduli that are to be used as seed in the batch backanalysis process in situations where there is the need to use more than one pavement section, due to varying layers, thicknesses or even geotechnical parameters. For example, in the following normalized D1 deflection graphic it is noticeable that there exist three distinct sections in this specific test line; this is a case where it would be best to backcalculate a random drop out of each of these three sections using the "From List" option of the single test menu, and to adjust three different sets of seed moduli for the batch analysis process in accordance to the backcalculated moduli and distance spans.

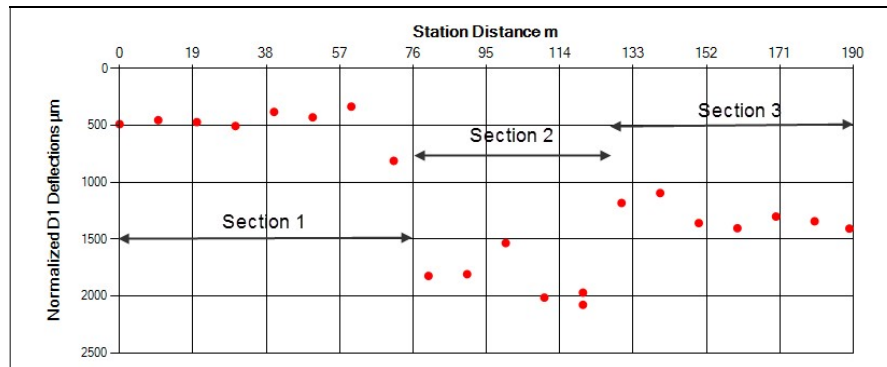


Figure 81 Pavement section division based on D1 sensor normalized deflections.

5.8.3. Average alignment drop single test

The single test window will also allow to determine and backcalculate the “average” drop of the selected test file, i.e., to determine a representative set of measured deflections and test load for each of the loaded alignments. Backcalculating these “average” deflections will enable the user to immediately establish a set of layer moduli that will be reasonably close to the mean layer moduli that will be obtained after processing all of the tests stated in the FWD files.

These “average” moduli will be very convenient to use as seed for the batch analysis, and also to define the best backcalculation model, thus enabling a faster backanalysis procedure of the test file data. The closer the seed values are to the real deformability moduli of the pavements layers (as well as the bedrock and subgrade modeling parameters), the faster the backcalculation process will be. The “average drop” backcalculated moduli are especially helpful if the test deflections are regular and uniform throughout the tested line as exemplified in the following figure.

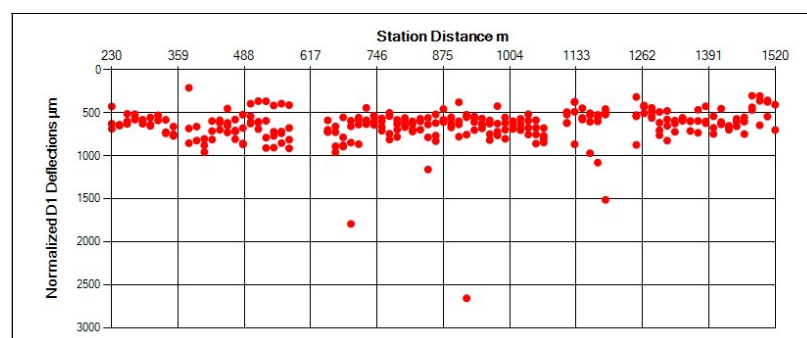


Figure 82 Uniform D1 sensor deflections.

To launch a single test window based on the “average” drop of the test file, it will not be necessary to have the Construction Data already defined, but if it is, this information will not be considered and automatically copied to the pavement section fields of the single test window, contrarily to the standard procedure of the “Drop from list” option.

5.9. Joint load transfer efficiency

Should the FWD raw data file(s) loaded by DAPS reflect tests in which the load transfer efficiency of jointed cement concrete pavements is being assessed, DAPS will automatically acknowledge this fact and process the corresponding information. DAPS presents the results of this evaluation in terms of the ratio between the highest and the lowest of the deflections measured in both slabs divided by the joint (percentage wise). This information is not directly related to the backcalculation batch analysis process, and therefore will be available immediately after the file(s) with data on sensors of negative offset have been loaded without the need to first define the correspondent construction data. To access this information and launch a separate window in which these results are presented, it is necessary to select the "Joint load transfer efficiency" option. It is possible to save these results to an ".xls" extension file, which will state one alignment per worksheet, just as described in the backcalculation batch analysis results.

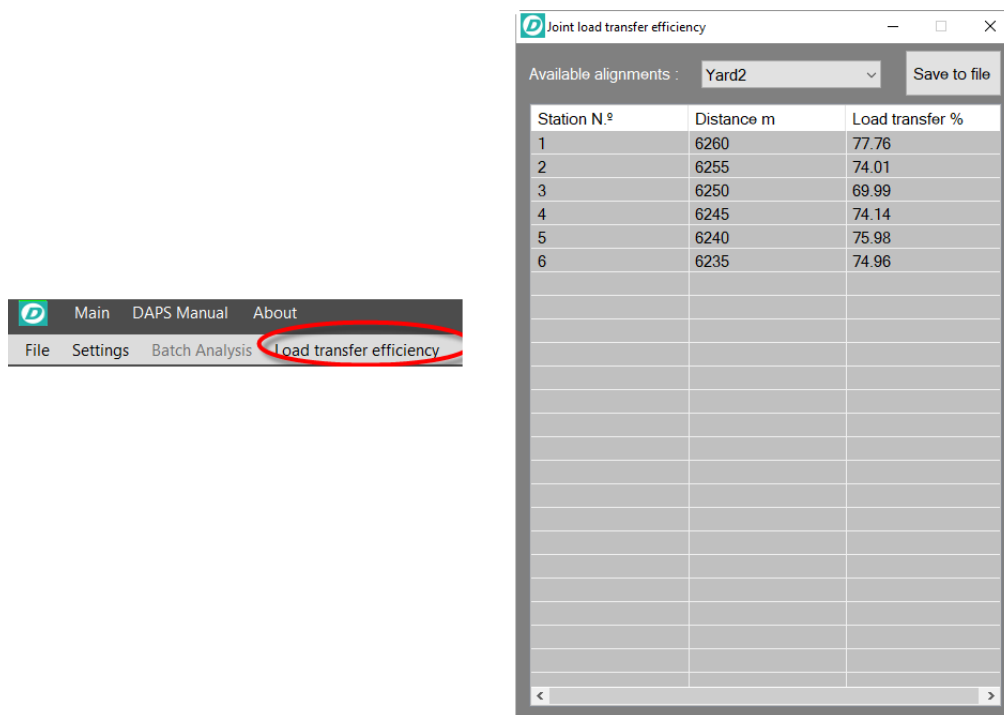


Figure 83 Joint load transfer efficiency window.

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