



## Technical Detailed Features

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## 1) DEEPXCAV TECHNICAL CAPABILITIES

DeepXcav™ analyzes the mechanical behavior of a flexible support structure of excavations in soil or rock, focusing on “local” soil-wall interaction aspects.

DeepXcav™ does not allow the user to study displacements of wide soil portions because rigid movements of the wall or of portions of soil cannot develop. Main goal of DeepXcav™ is then the calculation of bending moments, shears and lateral deformations of the supporting wall and the assessment of all other variables linked to these ones.

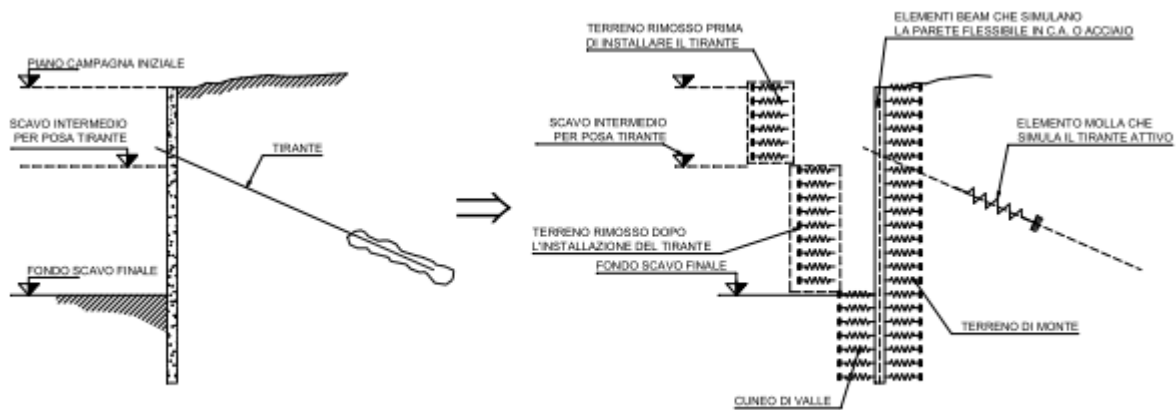
Flexible wall study is performed by means a numerical simulation of reality: the software builds and solves an algebraic equation linear system which solution reproduces realistically the support wall behavior.

The numerical simulation used follows two different paths:

- Conventional analysis
- Non-linear analysis according to an elasto-plastic spring model simulating soil.

### 1.a Non-linear analysis

DeepXcav™ uses a Finite element approach. A plane problem is analyzed (plane Y-Z) where active nodal degrees of freedom are lateral displacement and out-of-plane rotation. Vertical displacement are automatically constrained. Vertical support wall is meshed in vertical BEAM finite elements.



The soil, pushing against the wall (both uphill and downhill) and reacting in a complex way to the wall deformations, is simulated by means of a double elasto-plastic spring bed linked to the wall nodes. Tiebacks, trusses, slabs, deformable or rigid supports are modeled by point springs applied at the wall nodes.

DeepXcav™ analyzes the response, during the various realization phases, of a wall characterized in details (height, embedment, thickness, tiebacks, etc.), defined by the user before starting the calculation.

DeepXcav™ is not only an analysis software but has various procedures to generate design approaches (load combinations), structural and geotechnical checking according to the most important international Codes. In particular the following verifications are performed:

- structural design (STR) of the main structural elements (diaphragm, tiebacks, slabs, trusses, etc.)
- geotechnical design GEO (tieback pull-out, sub-grade stability, etc.)

The wall design must be performed in an iterative way: after knowing the results obtained with each analysis, the beginning hypothesized scheme is modified till a satisfactory solution is reached. The designer, according to his own experience, must detect the aspects deserving more attention during the structural optimization phase and establish criteria on the basis of which a design choice can be considered correct. DeepXcav™ does not offer any own design criterion and does not judge directly the analyzed scheme; it restricts itself to offer, in the most exhaustive and clear way, all the judgment tools. #1

## 2) THE NON-LINEAR SOIL MODEL

Two are soil models available:

### 2.a Sand or granular type

It is assumed that the vertical and horizontal effective stress components,  $\sigma_v$  e  $\sigma_h$ , are the principal stresses. In a stress plane a yield function and a hardening rule are defined. With reference to such a plane, three phase conditions (or states) are possible:

- Elastic phase (unloading reloading UR LR phase) : the soil element behaves elastically; this state corresponds with an unloading or reloading condition in the soil, whose stress is currently less than or equal to some previous stress level
- Hardening phase (Virgin compression phase or V-C): the stress state is increasing beyond maximum stress level in the previous step. A strain hardening behaviour is assigned during this phase and the element stiffness is still represented by a non zero value.
- Yielding: the minimum (active) or maximum (passive) horizontal stress is reached and the element behaves as a plastic material.

To set up the initial stress state at the beginning of the analysis, the effective vertical stress at each depth is computed based on the free field elevation, on the surcharge and on the water level. The horizontal stress is then recovered using the at rest coefficient  $K_0$ . The contributions due to point loads are then added.

To establish the initial element phase (whether the element is in UR-LR or V-C phase), the overconsolidation ratio OCR the normally consolidated at rest coefficient  $K_{NC}$ .

### 2.b Clay model

The constitutive model for clays describes the limit conditions based on effective resistance parameters only, and allows the simulation of both drained and undrained conditions, as well as the transition between them.

In drained conditions, this model is very similar to the model for granular soils. The only difference lays in the apparent cohesion parameter  $c'$ , which is now a varying parameter with the preconsolidation level, whereas for granular soils is a fixed User's input value. During undrained conditions, both effective stress path (ESP) and total stress path (TSP) are computed and the previous one is monitored to check limit conditions. The ESP evolution is highly affected by the imposed constraint on the volumetric deformation which must be null in such conditions. Since both ESP and TSP can be computed, the pore pressure change within the saturated soil in undrained condition can be easily computed as well.

### 2.c Conventional analysis

Classic conventional analysis can be performed through different ways:

- Classical Peck 1969 Earth Pressure Envelopes.
- FHWA Apparent Earth Pressures method
- FHWA Recommended method for apparent Earth Pressure Diagram for Soft to Medium Clays
- FHWA Loading method for Stratified Soil Profiles

## 3) SLOPED SURFACES

Current version of DeepXcav can handle both single angle sloped surfaces (i.e single 10degree slope angle) and complex benches with multiple points. DeepXcav automatically detects which condition applies.

For single angle slopes, DeepXcav will determine use the theoretical Rankine, Coulomb, or Caquot-Kerisel active, or passive lateral thrust coefficients (depending on user preference).

For non level ground that does not meet the single slope criteria, DeepXcav combines the solutions from a level ground with a wedge analysis approach. Pressures are generated in a two step approach: a) first, soil pressures are generated pretending that the surface is level, and then b) soil pressures are multiplied by the ratio of the total horizontal force calculated with the wedge method divided by the total horizontal force generated for a level ground solution. This is done incrementally at all nodes throughout the wall depth summing forces from the top of the wall.

Wall friction is ignored in the wedge solution but pressures with wall friction according to Coulomb for level ground are prorated as discussed.

#2

#### 4) GEOMETRICAL ISSUE

The problem is considered as a plane situation where a unit width slice of wall is analyzed, as shown in the following figure. Therefore, DeepXcav™ is not suitable for studying problems with important 3D effects.

Numerical modeling of wall-soil interaction is based on “BEAM ON ELASTIC PLASTIC SOIL” theory: wall is meshed with beam finite elements whose behavior is defined by the bending stiffness  $EJ$ , while soil is simulated by means of 1D elasto-plastic elements (springs) tied to the wall nodes: at each node one or two soil springs meet.



The limit for this scheme is to accept that each soil portion, schematized with a spring, behaves independently on the others nearby; the interaction among various soil regions depends on the wall bending stiffness only.

The realization of an excavation sustained by one or two walls, possibly with tiebacks, is simulated in all phases by means of an incremental static analysis: each load step coincides with a precise configuration characterized by an excavation height, by a number of tiebacks, by precise disposition of applied loads. Since finite element behavior is elasto-plastic, each configuration in general depends on the previous ones and plastic deformation development at a stage conditions the structure response in the following steps. The solution for each new configuration (step) is reached by means of an iterative calculation according to Newton-Raphson method.

The analysis has the goal to search the structural response in terms of lateral deformations of the wall during various steps and, hence, the soil horizontal pressure variation. In order to do this, it is necessary to define only two degrees of freedom in correspondence of each node, i.e. horizontal displacement and rotation around X axis orthogonal to the structure plane (positive if counterclockwise).

## 5) ACTIVE AND PASSIVE COEFFICIENTS OF LATERAL EARTH PRESSURES

The software offers a number of options for evaluating the “Active” and “Passive” coefficients that depend on the analysis method employed (non-linear or Conventional).

In the conventional analysis the software first determines which side is generating driving earth pressures. Once the driving side is determined, the software examines if a single ground surface angle is assumed on the driving and on the resisting sides. If a single surface angle is used then the exact theoretical equation is employed as outlined in. If an irregular ground surface angle is detected then the program starts performing a wedge analysis on the appropriate side. Horizontal ground earth pressures are then prorated to account for all applicable effects including wall friction. It should be noted that the active/passive wedge analyses can take into account flownet water pressures if a flownet is calculated.

The computed active and passive earth pressures are then modified if the user assumes another type of lateral earth pressure distribution (i.e. apparent earth pressure diagram computed from active earth pressures above subgrade, divide passive earth pressures by a safety factor, etc.).

All of the above  $K_a/K_p$  computations are performed automatically for each stage. The user has only to select the appropriate wall friction behavior and earth pressure distribution.

The non-linear solver active and passive earth pressure coefficients are controlled through the soils data. The software offers a different, more rationalized approach. The default  $K_a/K_p$  (for both  $\phi_{peak}$  and  $\phi_{cv}$ ) defined in the soils tab are evaluated by default, computed with no wall friction and for a horizontal ground surface. The user still has the ability to use the default PARATIE engine  $K_a/K_p$  by selecting a check box in the settings (Tabulated Butee values). This new approach offers the benefit that the same soil type can easily be reused in different design sections without having to modify the base soil properties. Otherwise, wall friction and ground surface angle can be incorporated within the default  $K_a/K_p$  values in the Soil Data Dialog.

## 6) GROUND WATER ANALYSIS METHODS

The software offers the following options for modeling groundwater:

- Hydrostatic: Applicable for both conventional and non-linear analysis. In non-linear, hydrostatic conditions are modeled by extending the “wall lining” effect to 100 times the wall length below the wall bottom.
- Simplified flow: Applicable for both conventional and Paratie analysis. This is a simplified 1D flow around the wall. In the non-linear analysis mode, monodimensional water flow scheme option is employed.
- Full Flow Net analysis: Applicable for both conventional and non-linear analysis. Water pressures are determined by performing a 2D finite difference flow analysis. The flownet analysis does not account for a drop in the phreatic line.
- User pressures: Applicable for both conventional and non-linear analysis. Water pressures defined by the user are assumed.

## 7) TYPICAL ANALYSIS STAGE

In the following the typical phases of excavation modeled by DeepXcav™ are described. The software great flexibility allows the user to deal with different simulation possibilities.

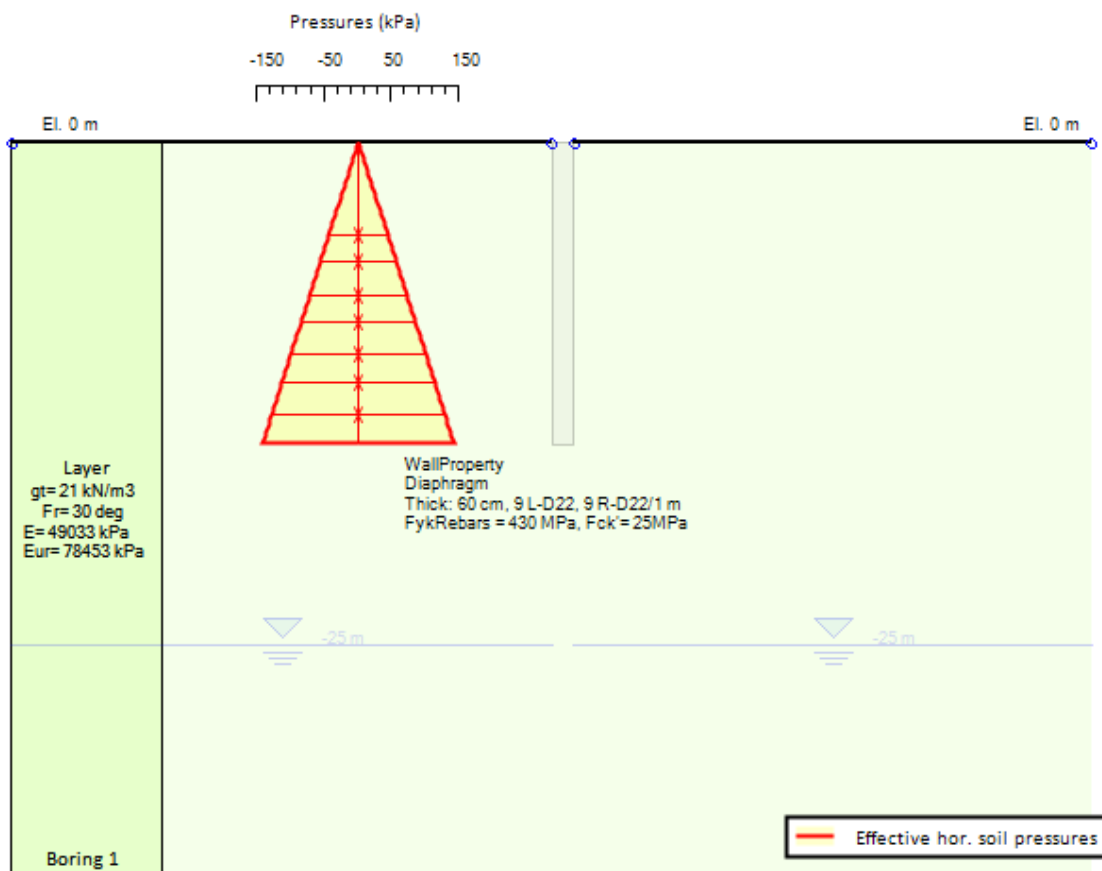
### 7.a Initial stage

Numerical simulation of a generic geotechnical problem requires an initial phase 0 where soil is assumed to be at rest, i.e. characterized by the stress state existing before any intervention. In DeepXcav™ the initial configuration is defined in a load step where all soil elements are present and balanced uphill and downhill; the sub-grade height, besides, coincides with the surface height and the water level must have the same value uphill and downhill.

The solution relative to the first step is characterized by a null displacement field which produces a null stress state in the beam elements simulating the wall. Instead, in the springs representing the soil a non-null stress state exists, however relative to non-disturbed conditions, i.e. vertical pressure, function of depth and of surcharges, and horizontal pressure depending on the vertical one through of  $K_0$ .

Initial pressures effects due to point surcharges, calculated by means of elasticity formulas, must be added to the horizontal pressure calculated as described above.

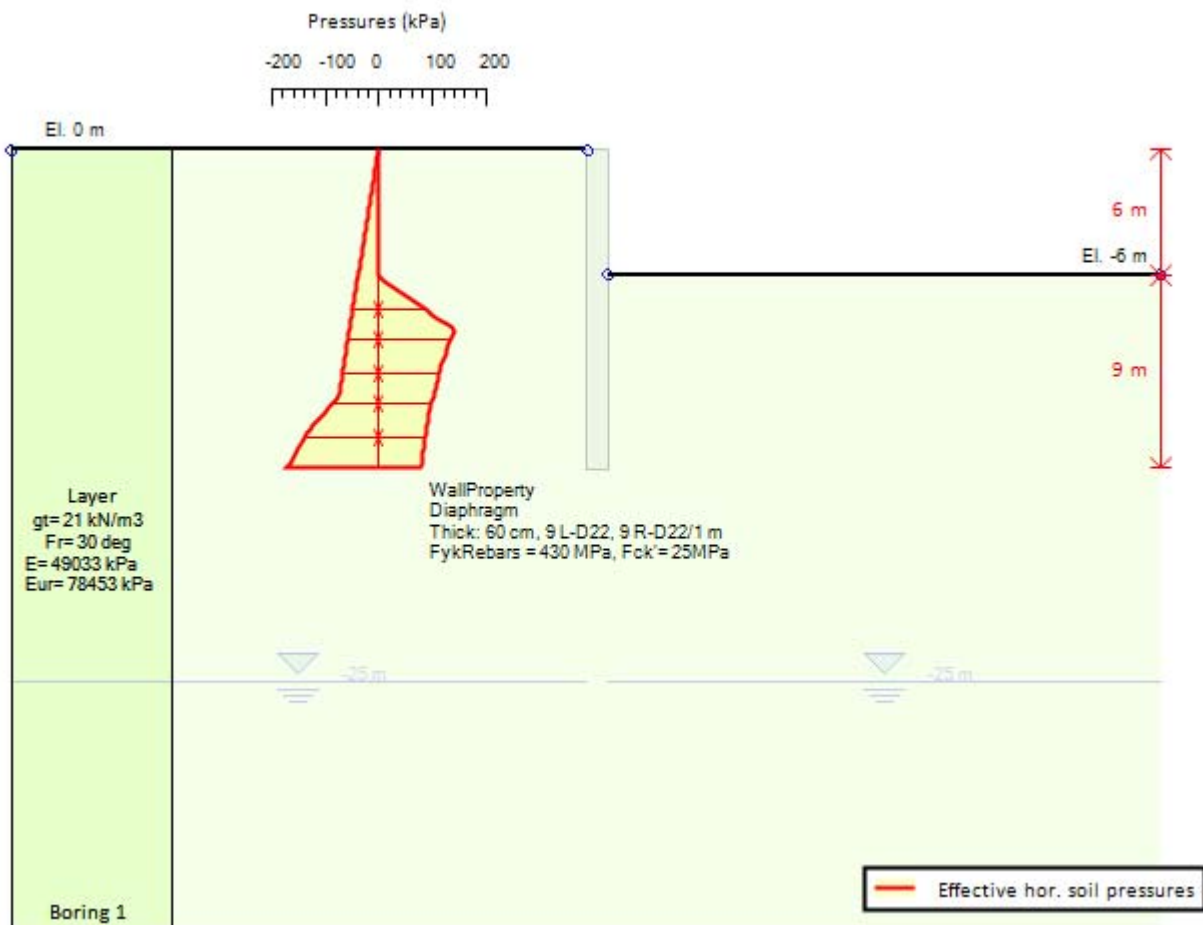
Practically, it is supposed that the wall construction, before the excavation, doesn't disturb the soil initial stress state much. Paratie solver phase 0 by two iteration at most: if more iterations are necessary, it means that input data are not properly defined.



#5

## 8) EXCAVATION STAGES

An incremental analysis step, coinciding with the reduction of the sub-grade height, is simulated as follows. A sub-grade level, lower than the one in the previous steps is assigned in this step; DeepXcav™ automatically removes the springs simulating soil above the sub-grade height, perturbing the equilibrium configuration in the previous phase. Equilibrium is re-established, by an iterative procedure, causing a variation of the deformation field. If it is not possible to reach a new configuration respectful of both equilibrium and soil failure condition, the iterative process does not converge.



During an excavation phase the drop of the water surface can be prescribed.

Besides, a buffer zone realization on the bottom of the excavation can be simulated by improving the characteristics of the natural soil, which is really done by means of various technologies as jet-grouting.

Simulation of fill-in

A soil portion, after removed, can be re-activated: in this way a fill-in is simulated. The stress state in the springs just re-activated is calculated in the following way:

1. The vertical effective component is calculated by considering the geostatic contribute, the uniformly distributed surcharge and the effects due to possibly strip foundations, according to the criteria in chapter 9;
2. The vertical effective component is calculated by multiplying by  $K_0^{NC}$  the vertical effective stress due to the geostatic component and to the uniformly distributed surcharge, but not to the effects of possibly strip foundations;

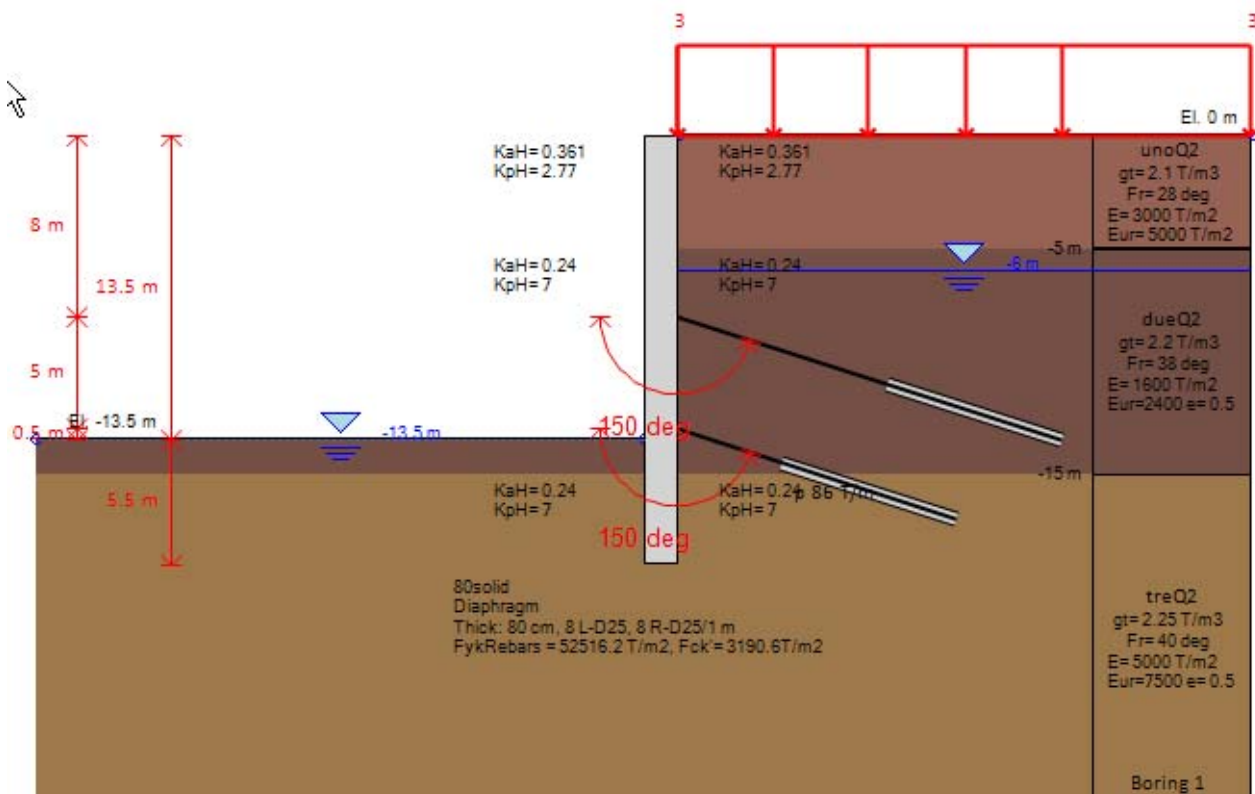
#6

### 3. Water pressure is assessed as other elements.

What explained above is relative to the first iteration of the fill-in step: in the end of the iterative process which leads to the balanced solution, the horizontal effective stress can differ from the at-rest thrust value, if the just re-activated soil is subjected to any deformation.

In order to assign a fill-in, it is sufficient to assign a sub-grade level higher than the one in the previous phase.

It is possible to simulate – approximately – compaction effects by applying and then removing a uniformly distributed surcharge.



## 9) APPLICATION OF TIEBACKS AND TRUSSES

The application of a row of tiebacks should be simulated in a step where no other changes are performed in the model. It is necessary in order to assess the effects of the tieback application without other collateral disturbing effects.

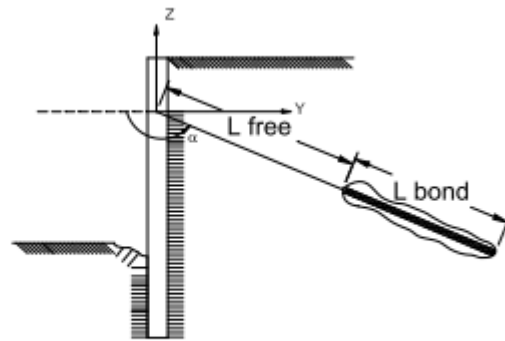
The tieback application is usually preceded by a phase where the excavation gets deeper, just below the height of the new support. This way, the true realization process is simulated quite realistically. Instead, by activating the tieback in the same time of the excavation deepening, the possibility of assessing an intermediate phase, which sometimes could be critic, is lost.

The tieback is a spring which is activated in this step and can be removed later. Its application causes two effects in the model:

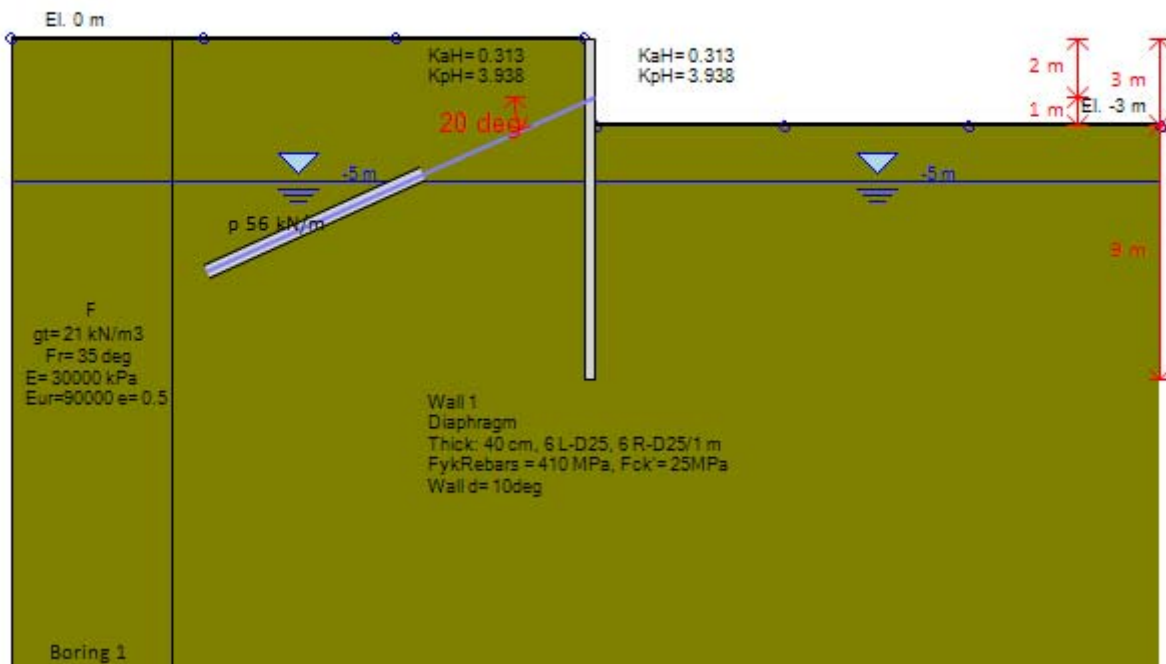
1. At the node in correspondence of the tieback application point a force is generated; this force is due to the possibly pre-tension characterizing this element;
2. The global structure stiffness receives a contribute due to the tieback extensional stiffness. When, in the subsequent stages, the node, where the tieback is connected, moves, the tieback force changes.

#7

An active tieback is also characterized by an axial stiffness, which can be calculated as:  
 $K=E(A/L)$ , where  $E$  is the steel Young modulus,  $A$  and  $L$  are the area and the length of the deformable tract respectively; the deformable tract length can be estimated as shown in the following:  
 If there is no initial pre-tension, no repercussions are on the model. Analogously, the simulation of a TRUSS or a SLAB, connecting points of two opposite diaphragms, doesn't cause changes and, therefore, it is not necessary to use a step to perform this operation only.



$$L = L_{\text{free}} + L_{\text{bond}} \times \eta \quad (\eta < 1)$$



For the TRUSS element it is possible to define a behavior “gap”, i.e. no resistance in traction.

Application of external surcharges and constraints

Generally, realization process simulation of a diaphragm doesn't need definition of external forces. The structure is stressed by the different distribution of soil actions uphill and downhill.

However, it is possible to define also external lateral forces, concentrated and distributed, varying them during the steps.

Finally, vertical surcharges are not treated as external loads, but they simply determine a geostatic state in soil.

DeepXcav™ allows the user to specify boundary conditions which impose specific values of displacement and rotation (absolute or incremental with respect to the step where the constraint has been activated) at a specific height. This option can be used for various purposes:

- rigid truss simulation;
- active tieback simulation.

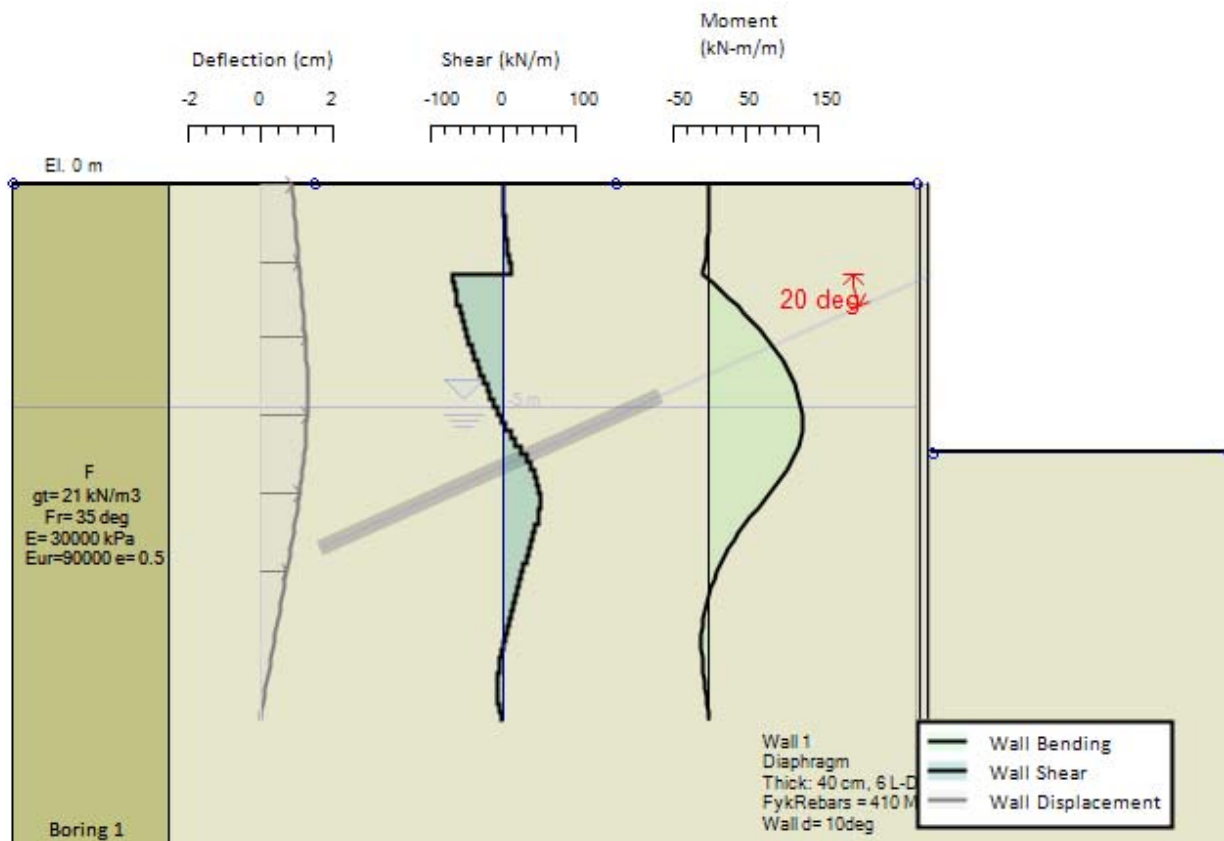
## 10) BIRTH / DEATH OPTION OF ELEMENTS

For all types of elements the User can easily decide the birth / death status. A tieback can be born at a specific stage and after several stages the designer could decide to neutralize its effect.

This tool allows the User to properly simulate the real excavation process also for very complex situations.

## 11) ANALYSIS RESULTS

A comprehensive list of diagrams and table are provided by the software at the end of each kind of analysis. The User can easily shows different diagrams in the same window in order to make the appropriate technical decisions.



## 12) DESIGN APPROACH AND CHECKING PROCEDURES

Eurocode 7 and other similar modern Codes recommends the designer examines a number of different Design Approaches (DA-1, DA-2, DA-3) so that the most critical condition is determined. In Eurocode 7 soil strengths are readjusted according to the material "M" tables, surcharges and permanent actions are readjusted according to the action "A" tables, and resistances are modified according to the "R" tabulated values. Hence, in a case that may be outlined as "A2" + "M2" + "R2" one would have to apply all the relevant factors to "Actions", "Materials", and "Resistances".

A designer also has to perform a service check in addition to all the ultimate design approach cases.

Hence, a considerable number of cases will have to be examined. In summary, EC7 provides the following combinations:

Design Approach 1, Combination 1: A1 "+" M1 "+" R1

Design Approach 1, Combination 2: A2 "+" M2 "+" R1

Design Approach 2: A1\* "+" M1 "+" R2

Design Approach 3: A1\* "+" A2+ "+" M2 "+" R3

#10

Where

A1\* = For structural actions or external loads, and A2+= for geotechnical actions

EQK (from EC8): M2 "+" R1

In Eurocode 7, various equilibrium and other type checks are examined:

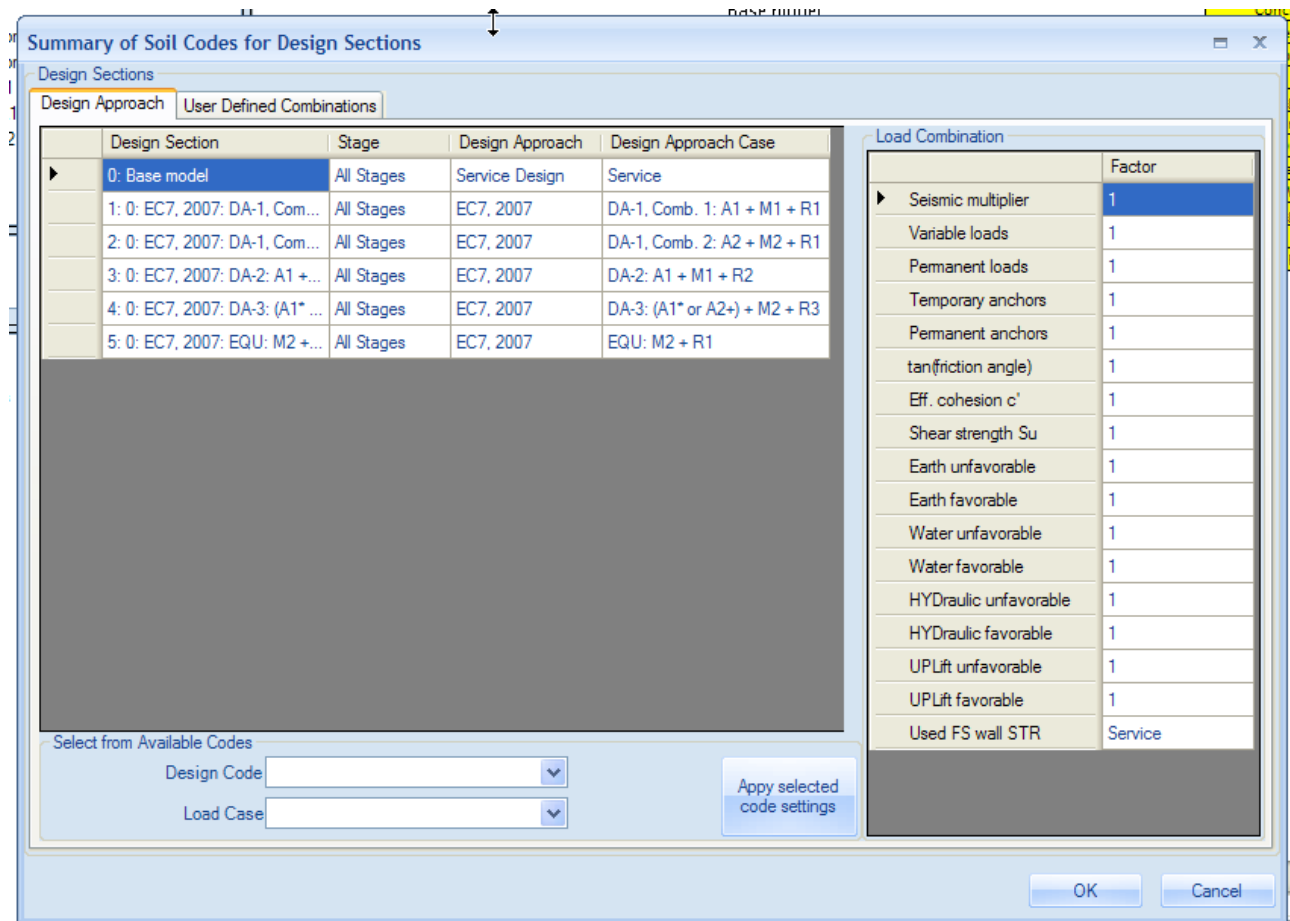
- a) STR: Structural design/equilibrium checks
- b) GEO: Geotechnical equilibrium checks
- c) HYD: Hydraulic heave cases
- d) UPL: Uplift
- e) EQU: Equilibrium states

All these approach can be easily automatically generated by the software.

The list of approaches are clearly reported in a unique window.

The user can also decide to follow different path:

- generate and analyze just one of the approaches
- generate an automatic approach , then change some parameters



All the approaches will be used for different type of checking, depending by the type of limit states to investigate. DeepXcav handles STR, GEO, and HYD checks.

#11

The type of checking performed are, for STR category:

- Combined (bending+axial) resistance , including buckling for steel sheet piles
- Shear resistance for concrete walls
- Simplified Bending + shear resistance for concrete slabs
- Axial resistance for struts, tiebacks
- Cracking, tension checking for concrete rectangular walls

for GEO category:

Toe embedment

DeepXcav uses classical methods in determining the toe embedment depth for a safety factor of 1.0 and the

available safety factor. The available methods for calculating toe stability for cantilever, single support, and multiple level braced walls are :

- Passive Resistance Safety Factor (Conventional Analysis):
- Rotational Safety Factor (Conventional Analysis):
- Length based (Conventional Analysis):
- Mobilized passive resistance (PARATIE)
- It is also possible to evaluate the mobilized passive resistance ratio.

In case of using the non-linear solver an iterative procedure that gradually reduces the wall length until the wall collapses is available . This procedure allows the User to properly evaluate embedment safety also for highly hyperstatic conditions.

- Anchor pull out

A ground anchor has two forms of capacity, a geotechnical and a structural resistance. The structural resistance of the tendons is defined by EC steel standards while the bonded zone has to be examined for its pull-out capacity (geotechnical check). The new software includes a number of ground anchor (tieback) sections. Hence, a ground anchor section can be reused over and over in many different support levels and in many different design sections (the same approach is also utilized for steel struts, rakers (inclined struts), and concrete slabs

For HYD

- Hydraulic gradient check

### 13) CHECKING RESULTS AND REPORT

All checking results are available in different ways:

- synthetic table with ultimate and serviceability checking ratio coefficients
- diagram ratio of the principal checking
- detailed document

**Analysis and Checking Summary**

Ka and Kp Calculation and Other Stage Values

For All Design Sections

Summary Extended View  
 Summary vs Design Section  
 Summary - Critical Items  
 Support Results  
 Wall Results  
 Max. Moment vs Stage  
 Max. Shear vs Stage  
 Max. Support F vs Stage  
**One Design Section**  
 Extended Summary  
 Support Force/S vs Stage  
 Support Force vs Stage  
 Embedment FS vs Stage  
 Support Check vs Stage  
 Forces (Res. F, M/Drive F, M)  
 Calc. Ka and Kp all stages  
 Reinforcement Requirements  
 Lagging (Estimate)  
 Basal, Clough, Settlement  
 Crack control summary  
 Launch Diagrams  
 Warnings (3)

**Used Soil Strength Parameters for Each Stage on Driving Side (Uphill)**

	Layer	Drained-Undrained	Method Description	Used Wall Delta (deg)	Used Soil Friction (deg)	Used c' (kPa)	Used Su (kPa)	Used KaH	Used KpH	Notes
0: Stage 0	F	Drained	* KaUH= FS_DriveEarth x [Coulomb_Kah(deg FR= 29.256, DFR= 10, Asur= 0)] = 1 x 0.313 = 0.313	0	29.256	0	0	0.313	3.938	RankineActual theor
1: Stage 1	F	Drained	* KaUH= FS_DriveEarth x [Coulomb_Kah(deg FR= 29.256, DFR= 10, Asur= 0)] = 1 x 0.313 = 0.313	10	29.256	0	0	0.313	3.938	DrainedActual theor
2: Stage 2	F	Drained	* KaUH= FS_DriveEarth x [Coulomb_Kah(deg FR= 29.256, DFR= 10, Asur= 0)] = 1 x 0.313 = 0.313	10	29.256	0	0	0.313	3.938	DrainedActual theor
3: Stage 3	F	Drained	* KaUH= FS_DriveEarth x [Coulomb_Kah(deg FR= 29.256, DFR= 10, Asur= 0)] = 1 x 0.313 = 0.313	10	29.256	0	0	0.313	3.938	DrainedActual theor

\* KaUH= FS\_DriveEarth x

**Used Soil Strength Parameters for Each Stage on Resisting Side (Downhill)**

	Layer	Drained-Undrained	Method Description	Used Wall Delta (deg)	Used Soil Friction (deg)	Used c' (kPa)	Used Su (kPa)	Used KaH	Used KpH	Notes
0: Stage 0	F	Drained	* KpDH= [1/FS_Resist] x [Coulomb_Kph(deg FR= 29.256, DFR= 10, Asur= 0)] => * KpDH = [1 / 1] x [3.938] = 3.938	10	29.256	0	0	0.313	3.938	RankineActual theor
1: Stage 1	F	Drained	* KpDH= [1/FS_Resist] x [Coulomb_Kph(deg FR= 29.256, DFR= 10, Asur= 0)] => * KpDH = [1 / 1] x [3.938] = 3.938	10	29.256	0	0	0.313	3.938	DrainedActual theory
2: Stage 2	F	Drained	* KpDH= [1/FS_Resist] x [Coulomb_Kph(deg FR= 29.256, DFR= 10, Asur= 0)] => * KpDH = [1 / 1] x [3.938] = 3.938	10	29.256	0	0	0.313	3.938	DrainedActual theory

\* KpDH= [1/FS\_Resist] x

Available Design Sections: 0: Design Section  
 Select Wall: 0: Wall 1  
 Copy Table Data    Exit

#### 14) DETAILED CHECKING REPORT DOCUMENTS

A parte from the graphic checking tools, for the principal checkings, the program provides specific detailed Text documents. These documents provide a step by step resume of all the used formulas including where necessary the paragraph of the code.

