OPTUM COMPUTATIONAL ENGINEERING

**Optum G2**

Version 1.14

# RESULTS

Optum G2: Results

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# Contents

# 1 GENERAL INFORMATION

The results of the analyses can be visualized using the tools under Results ribbon. Plots of both variables associated with solid domains (stresses, displacements, etc) and variables associated with structural elements (bending moments, displacements, etc) may be plotted. Detailed point information about either category of variables can be obtained by mouse click anywhere in the domain (see figure below).

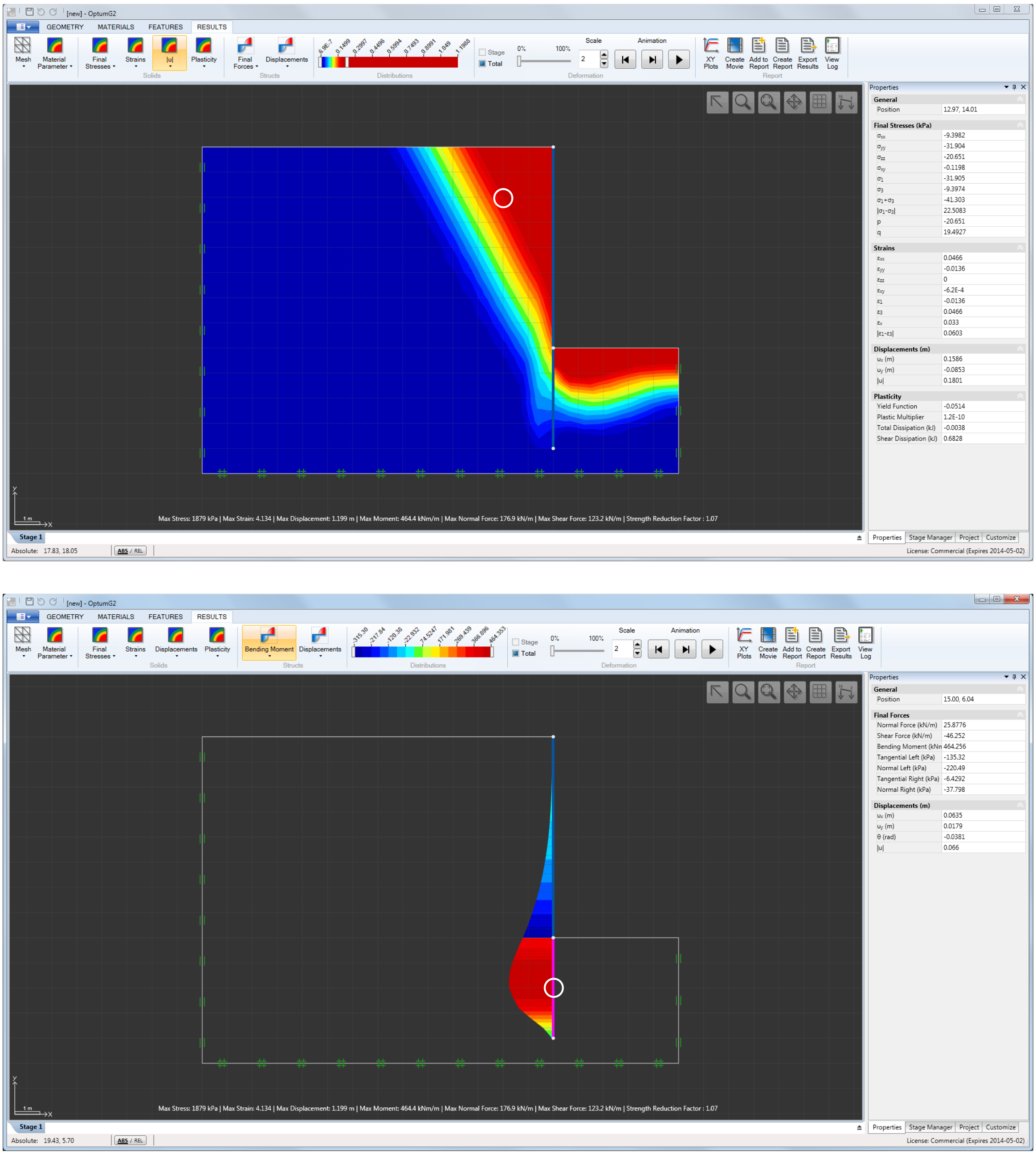

Figure 1.1: Results associated with solid domains (top) and with structural elements (bottom). The white circles indicated the position (determined by mouse click) corresponding to the results shown in the property window on the right.

# 2 SOLIDS

## 2.1 Stresses

In OptumG2, stress sets are available: Initial Stresses and Final Stresses. The former set are the initial stresses at the beginning of the analysis while the latter are the stresses that follow as a result of the analysis. Depending on the settings of a given analysis, the initial stresses may be calculated automatically or they may be transferred from a previous stage. In the latter case, the stresses are mapped from one mesh to another which may induce some slight artifacts. For example, the mere process of mapping stresses from one mesh to another may induce artificial deformations. However, in far most cases these are several orders of magnitude less than the actual deformations resulting from the application of load, removal of material, etc.

Following Terzhagi's principle for fluid saturated media, the total stress is the sum of the effective stress, and the pressure of the pore fluid:

$$\boldsymbol{\sigma} = \boldsymbol{\sigma}' + \mathbf{m}p_f \tag{2.1}$$

where

$\boldsymbol{\sigma}$ = Total stress

$\boldsymbol{\sigma}'$ = Effective stress

$p_f$ = Pore pressure

$\mathbf{m} = (1, 1, 1, 0)^T$ in plane strain.

Depending on the type of analysis, both these types of stresses may be available in the Initial and Final Stresses results sets. The quantities in the two sets are:

**Total Stresses**

| Variable | Unit | Description |
|---|---|---|
| $\sigma_{xx}$, $\sigma_{yy}$, $\sigma_{zz}$ | kPa | Total normal stresses in the $x$, $y$, and $z$ directions |
| $\tau_{xy}$ | kPa | Total shear stress on $x$-$y$ planes |
| $\sigma_1, \sigma_3$ | kPa | Principal total stresses ordered so that $\sigma_1 \leq \sigma_3$. Hence, for problems where both principal stresses are compressive, we have $\lvert\sigma_1\rvert \geq \lvert\sigma_3\rvert$ |
| $\sigma_1 + \sigma_3$ | kPa | Mohr-Coulomb measure of mean total stress |
| $\sigma_1 - \sigma_3$ | kPa | Mohr-Coulomb measure of deviatoric total stress |
| $p$ | kPa | Hydrostatic total pressure and Drucker-Prager measure of total mean stress $p = \frac{1}{3}(\sigma_x + \sigma_y + \sigma_z)$. |
| $q$ | kPa | Drucker-Prager measure of deviatoric stress, $q = \sqrt{\frac{1}{2}(\sigma_{xx} - \sigma_{yy})^2 + \frac{1}{2}(\sigma_{yy} - \sigma_{zz})^2 + \frac{1}{2}(\sigma_{zz} - \sigma_{xx})^2 + 3\tau_{xy}^2}$ |
| $\sigma_1, \sigma_3$ vectors | – | Vector plot showing direction and magnitude of principal total stresses, $\sigma_1$ red and $\sigma_3$ in blue |

### Effective Stresses

| Variable | Unit | Description |
|---|---|---|
| $\sigma'_{xx}$, $\sigma'_{yy}$, $\sigma'_{zz}$ | kPa | Effective normal stresses in the $x$, $y$, and $z$ directions |
| $\sigma'_{xy}$ | kPa | Effective shear stress on $x$-$y$ planes. Equal to the total shear stress, $\sigma'_{xy} = \sigma_{xy}$ |
| $\sigma'_1, \sigma'_3$ | kPa | Principal effective stresses ordered so that $\sigma'_1 \leq \sigma'_3$. Hence, for problems where both principal stresses are compressive, we have $\lvert\sigma'_1\rvert \geq \lvert\sigma'_3\rvert$ |
| $\sigma'_1 + \sigma'_3$ | kPa | Mohr-Coulomb measure of mean effective stress |
| $\sigma'_1 - \sigma'_3$ | kPa | Mohr-Coulomb measure of deviatoric effective stress |
| $p'$ | kPa | Hydrostatic total pressure and Drucker-Prager measure of mean total stress, $p = \frac{1}{3}(\sigma'_x + \sigma'_y + \sigma'_z)$. |
| $q$ | kPa | Drucker-Prager measure of deviatoric stress, $q' = \sqrt{\frac{1}{2}(\sigma'_{xx} - \sigma'_{yy})^2 + \frac{1}{2}(\sigma'_{yy} - \sigma'_{zz})^2 + \frac{1}{2}(\sigma'_{zz} - \sigma'_{xx})^2 + 3{\tau'_{xy}}^2} = q$ |
| $\sigma'_1, \sigma'_3$ vectors | – | Vector plot showing direction and magnitude of principal effective stresses, $\sigma'_1$ red and $\sigma'_3$ in blue |

### Undrained Shear

| Variable | Unit | Description |
|---|---|---|
| $c_u$ | kPa | Undrained shear strength according to the Tresca criterion $\lvert\sigma_1 - \sigma_3\rvert = 2c_u$. Available under Initial Stresses for stages with Time Scope = Short Term. |

Note: for Limit Analysis and Strength Reduction only Total Stresses are available in the Results ribbon even though both steady state and excess pore pressures may be part of the calculation.

## 2.2 Strains

Strains derive from displacements assuming infinitesimal deformations. In plane strain we have

$$\begin{aligned} \varepsilon_{xx} &= \frac{\partial u_x}{\partial x} \\ \varepsilon_{yy} &= \frac{\partial u_y}{\partial y} \\ \varepsilon_{zz} &= 0 \\ \varepsilon_{xy} &= \frac{\partial u_x}{\partial y} + \frac{\partial u_y}{\partial x} \end{aligned} \tag{2.2}$$

where $\boldsymbol{\varepsilon} = (\varepsilon_{xx}, \varepsilon_{yy}, \varepsilon_{zz}, \varepsilon_{xy})^{\mathsf{T}}$ are the strains and $\mathbf{u} = (u_x, u_y)^{\mathsf{T}}$ are the displacements.

In general, a distinction must be made between elastic and plastic strains. These add up to the total strains:

$$\boldsymbol{\varepsilon} = \boldsymbol{\varepsilon}^e + \boldsymbol{\varepsilon}^p \tag{2.3}$$

where

$\boldsymbol{\varepsilon}$ = Total strains

$\boldsymbol{\varepsilon}^e$ = Elastic strains

$\boldsymbol{\varepsilon}^p$ = Plastic strains

In OptumG2, the following quantities related to total and plastic strains are available in the Results ribbon:

**Total Strains**

| Variable | Unit | Description |
|---|---|---|
| $\varepsilon_{xx}$, $\varepsilon_{yy}$, $\varepsilon_{zz}$ | – | Total normal strains in the $x$, $y$, and $z$ directions |
| $\tau_{xy}$ | – | Total shear strains on $x$-$y$ planes |
| $\varepsilon_1, \varepsilon_3$ | – | Principal total strains ordered so that $\varepsilon_1 \leq \varepsilon_3$. Hence, for problems where both principal strains are compressive, we have $\lvert\varepsilon_1\rvert \geq \lvert\varepsilon_3\rvert$ |
| $\varepsilon_v$ | – | Volumetric total strain, $\varepsilon_v = \varepsilon_{xx} + \varepsilon_{yy} + \varepsilon_{zz} = \varepsilon_1 + \varepsilon_3$ |
| $\lvert\varepsilon_1 - \varepsilon_3\rvert$ | – | Deviatoric total strain |
| $\varepsilon_1, \varepsilon_3$ vectors | – | Vector plot showing direction and magnitude of principal total strain, $\varepsilon_1$ in red and $\varepsilon_3$ in blue |

### Plastic Strains

| Variable | Unit | Description |
|---|---|---|
| $\varepsilon_{xx,p}$, $\varepsilon_{yy,p}$, $\varepsilon_{zz,p}$ | – | Plastic normal strains in the $x$, $y$, and $z$ directions |
| $\tau_{xy,p}$ | – | Plastic shear strains on $x$-$y$ planes |
| $\varepsilon_{1,p}, \varepsilon_{3,p}$ | – | Principal plastic strains ordered so that $\varepsilon_{1,p} \leq \varepsilon_{3,p}$. Hence, for problems where both principal strains are compressive, we have $\lvert\varepsilon_{1,p}\rvert \geq \lvert\varepsilon_{3,p}\rvert$ |
| $\varepsilon_{v,p}$ | – | Volumetric plastic strain, $\varepsilon_{v,p} = \varepsilon_{xx,p} + \varepsilon_{yy,p} + \varepsilon_{zz,p} = \varepsilon_{1,p} + \varepsilon_{3,p}$ |
| $\lvert\varepsilon_{1,p} - \varepsilon_{3,p}\rvert$ | – | Deviatoric plastic strain |
| $\varepsilon_{1,p}, \varepsilon_{3,p}$ vectors | – | Vector plot showing direction and magnitude of principal total strain, $\varepsilon_{1,p}$ in red and $\varepsilon_{3,p}$ in blue |

Note: for Limit Analysis and Strength Reduction, the difference between total and plastic strains is immaterial. In such cases, only Total Strains are available in the Results ribbon.

## 2.3 Displacements

OptumG2 operates with two types of displacements: Stage Displacements and Total Displacements. The former are the displacements incurred in the given stage while the latter are the accumulation of former. It should be noted that the small deformation assumption is used throughout. As such, all operations involving the removal of material, addition of structural elements, etc. are referenced to the original geometry, i.e. neglecting the effects of the displacements on the geometry. As an example, if an anchor is added to a sheet pile wall that has already undergone displacements, the anchor should be added with reference to the original geometry, disregarding the fact that this has changed slightly as a result of the deformations.

The following displacement quantities are available in the Results ribbon:

**Stage Displacements**

| Variable | Unit | Description |
|---|---|---|
| $\Delta u_x$ | m | Stage displacements in the $x$-direction |
| $\Delta u_y$ | m | Stage displacements in the $y$-direction |
| $\Delta u$ vector | – | Stage displacement vectors |

**Total Displacements**

| Variable | Unit | Description |
|---|---|---|
| $u$ | m | Total displacements in the $x$-direction |
| $u$ | m | Total displacements in the $y$-direction |
| $u$ vector | – | Total displacement vectors |

Note: for Limit Analysis and Strength Reduction, the difference between total and stage displacements is immaterial. In such cases, only Total Displacements are available in the Results ribbon.

## 2.4 Plasticity

This results set contains various quantities related to plasticity and plastic deformations.

Recall that the stress are limited by the yield function:

$$F(\boldsymbol{\sigma}', \boldsymbol{\kappa}) \leq 0 \tag{2.4}$$

where $F$ is the yield function, $\boldsymbol{\sigma}'$ are the effective stresses and $\boldsymbol{\kappa}$ is a set of stress-like hardening variables.

Further recall that the plastic strain rates follow from the flow rule:

$$d\boldsymbol{\varepsilon}^p = \lambda \frac{\partial G}{\partial \boldsymbol{\sigma}'} \tag{2.5}$$

where $d\boldsymbol{\varepsilon}^p$ are the plastic strain increments, $G$ is the plastic potential (which may or may not be equal to the yield function $F$), and $\lambda \geq 0$ is the plastic multiplier. Assuming that the magnitude of $\partial G/\partial \boldsymbol{\sigma}'$ is independent of, or insensitive to, the magnitude of $\boldsymbol{\sigma}'$ (which is usually the case), the plastic multiplier $\lambda$ is a direct measure of the magnitude of the plastic strain increment.

Another central quantity to plastic deformation is the dissipation:

$$D = \int_V \boldsymbol{\sigma}^{\mathsf{T}} d\boldsymbol{\varepsilon}^p \, \mathrm{d}V \tag{2.6}$$

Again, this quantity is a direct measure of the intensity of the plastic straining over a volume $V$.

While the dissipation often is a good indicator of the intensity of plastic deformation, it does occasionally fail in this regard. In particular, for purely frictional materials with an associated flow rule, it may be shown that $D = 0$. In such cases, the shear dissipation provides a more useful indicator of plasticity. This quantity is defined as:

$$D_s = \int_V \boldsymbol{\sigma}_s^{\mathsf{T}} d\boldsymbol{\varepsilon}_s^p \, \mathrm{d}V \tag{2.7}$$

where

$$\begin{aligned} \boldsymbol{\sigma}_s &= \boldsymbol{\sigma} - \mathbf{m}p \\ \boldsymbol{\varepsilon}_s^p &= \boldsymbol{\varepsilon}^p - \tfrac{1}{3}\mathbf{m}\varepsilon_v^p \end{aligned} \tag{2.8}$$

are the deviatoric stress and strain respectively ($p$ and $\varepsilon_v^p$ being the hydrostatic pressure and volumetric plastic strain respectively).

The following quantities related to plasticity are available in the Results ribbon:

### Plasticity

| Variable | Unit | Description |
|---|---|---|
| Yield Function | kPa | See discussion above |
| Plastic Multiplier | – | See discussion above |
| Total Dissipation | kJ | See discussion above |
| Shear Dissipation | kJ | See discussion above |

Note: in Limit Analysis and Strength Reduction, the total strains are equal to the incremental plastic strains which are used in place of $d\varepsilon^p$ in the above.

## 2.5 Pore Pressures

Two types of pore pressures are accounted for in OptumG2 those resulting from seepage and those generated as a result of mechanical deformation under undrained conditions (for analyses with Time Scope = Short Term and Drained/Undrained materials).

The following quantities are available in the Results ribbon:

### Seepage Pressures

| Variable | Unit | Description |
|---|---|---|
| $p_s$ | kPa | Seepage pressure |
| $h_s$ | m | Seepage pressure head, $h_s = y - p_s/\gamma_w$ with $y$ being the vertical coordinate and $\gamma_w = 9.8\,\mathrm{m/s^2}$ |
| $S$ | – | Degree of saturation in accordance with the hydraulic model used |

### Effective Unit Weights

| Variable | Unit | Description |
|---|---|---|
| $\gamma'_x$ | $\mathrm{kN/m^3}$ | Horizontal effective unit weight, $\gamma'_x = \gamma_{\mathrm{sat}} - \partial p_s/\partial x$ |
| $\gamma'_y$ | $\mathrm{kN/m^3}$ | Vertical effective unit weight, $\gamma'_y = \gamma_{\mathrm{sat}} - \partial p_s/\partial y$ |

### Excess Pressures

| Variable | Unit | Description |
|---|---|---|
| $p_e$ | kPa | Excess pore pressure |
| $h_e$ | m | Excess pore pressure head |

### Fluxes

| Variable | Unit | Description |
|---|---|---|
| $q_x$ | m/day | Fluid velocity in the $x$-direction |
| $q_y$ | m/day | Fluid velocity in the $y$-direction |
| $q$ vector | – | Fluid velocity vector |
| $q_n$ | $\mathrm{m^3/day/m}$ | Nodal flux (only relevant on boundaries, otherwise equal to zero) |

# 3 STRUCTS

For problems involving structural elements, a separate category, Structs, appears in the Results ribbon.

Structural elements also involve a distinction between the left and right sides. These are defined as shown in Figure 3.1. Note that the interface ⊖ and ⊕ symbols indicate the left and right sides respectively. Following conventional sign notations, bending moments are positive when they generate tension on the right side of the beam.

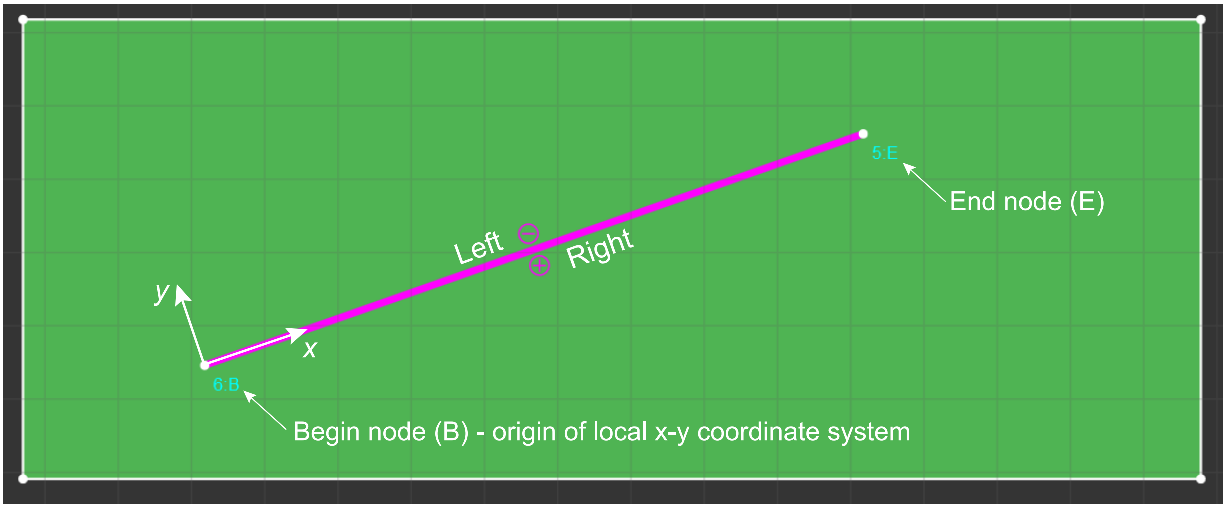


Figure 3.1: Orientation of structural elements.

## 3.1 Forces

In analogy with stresses in solids, both Initial Forces and Final Forces are available (when relevant) in the Results ribbon. These result sets contain the following variables:

### Sectional Forces

| Variable | Unit | Description |
|---|---|---|
| Normal Force | kN/m | Positive in tension |
| Shear Force | kN/m | Derivative of bending moment with respect to local $x$-coordinate |
| Bending Moment | kNm/m | Positive corresponding to tension on the right side of the beam |

### Earth Pressures

| Variable | Unit | Description |
|---|---|---|
| Tangential Left | kN/m$^2$ | Sign consistent with solid shear stress |
| Normal Left | kN/m$^2$ | Sign consistent with solid normal stress (positive in tension) |
| Tangential Right | kN/m$^2$ | Sign consistent with solid shear stress |
| Normal Right | kN/m$^2$ | Sign consistent with solid normal stress (positive in tension) |

## 3.2 Displacements

In analogy with solids, both Stage Displacements and Total Displacements are available. The following displacement quantities are available in the Results ribbon:

**Stage Displacements**

| Variable | Unit | Description |
|---|---|---|
| $\Delta u_x$ | m | Stage displacements in the $x$-direction |
| $\Delta u_y$ | m | Stage displacements in the $y$-direction |

**Total Displacements**

| Variable | Unit | Description |
|---|---|---|
| $u_x$ | m | Total displacements in the $x$-direction |
| $u_y$ | m | Total displacements in the $y$-direction |

Note: for Limit Analysis and Strength Reduction, the difference between total and stage displacements is immaterial. In such cases, only Total Displacements are available in the Results ribbon.