PLAXIS 2D

CONNECT Edition V22.02

NATM Tunneling - Beta Method: Incomplete Staged construction method vs Deconfinement method

Bentley Advancing Infrastructure

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1 Introduction

The New Austrian Tunnelling method (NATM) was developed in Austria between 1957 to 1965 as a method for tunnel construction in the Alps. The main purpose of developing NATM was to construct tunnels at a high depth, where larger in situ soil stresses are present. The NATM is a technique in which the ground that is exposed by an excavation is stabilized with shotcrete to form a temporary lining. Some of the advantages of NATM are the rapid and consistent support of freshly excavated ground and the easier construction of complex intersections.

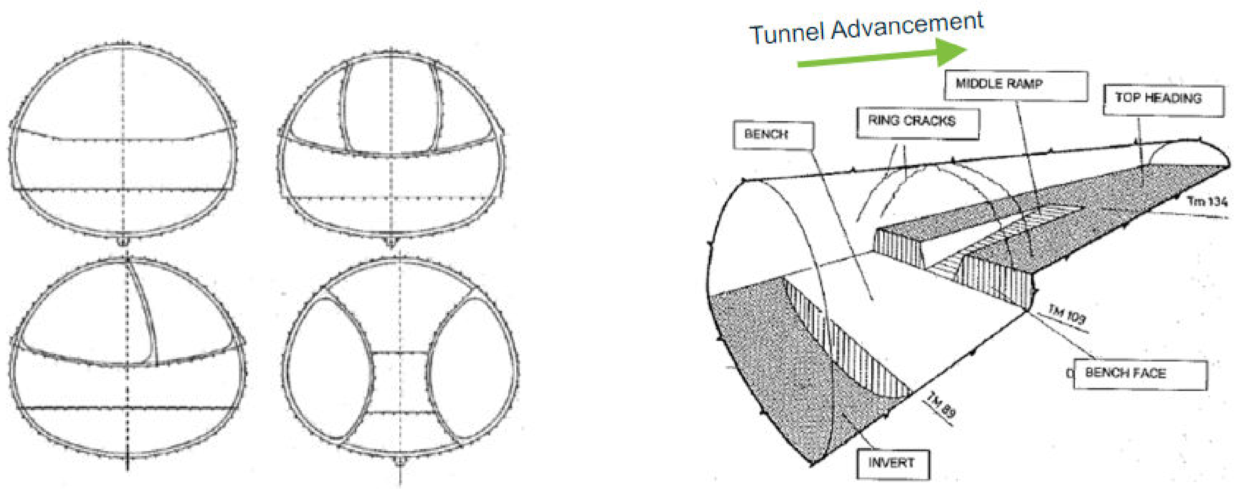


Figure 1: NATM construction process

In the NATM method, the tunnel is excavated in parts over a certain length; hence the tunnel is in various stages of completeness over the entire construction. Part of the stability in the NATM method relies on the fact, that the ground if allowed to deform slightly, is capable of contributing to its own support. For this reason, the NATM is a method where the surrounding rock or soil of a tunnel are integrated into an overall arch or ring, becoming themselves part of the support structure. The NATM method utilises this effect systematically for its development, but also uses modern means of monitoring and support, such as shotcrete and rock bolts, to guarantee the stability during the tunnel construction.

In practice, during construction, a tunnel is unsupported over a limited length behind the advancement front. However, in a 2D model a tunnel excavation would mean that the ground is left unsupported over an infinite length which might lead to failure in the absence of three-dimensional arching effect. To overcome this limitation of 2D modelling and to account for the effects of the third dimension on the excavation within finite element analysis framework, the Convergence-confinement method or ***Beta-method*** *is widely used.*

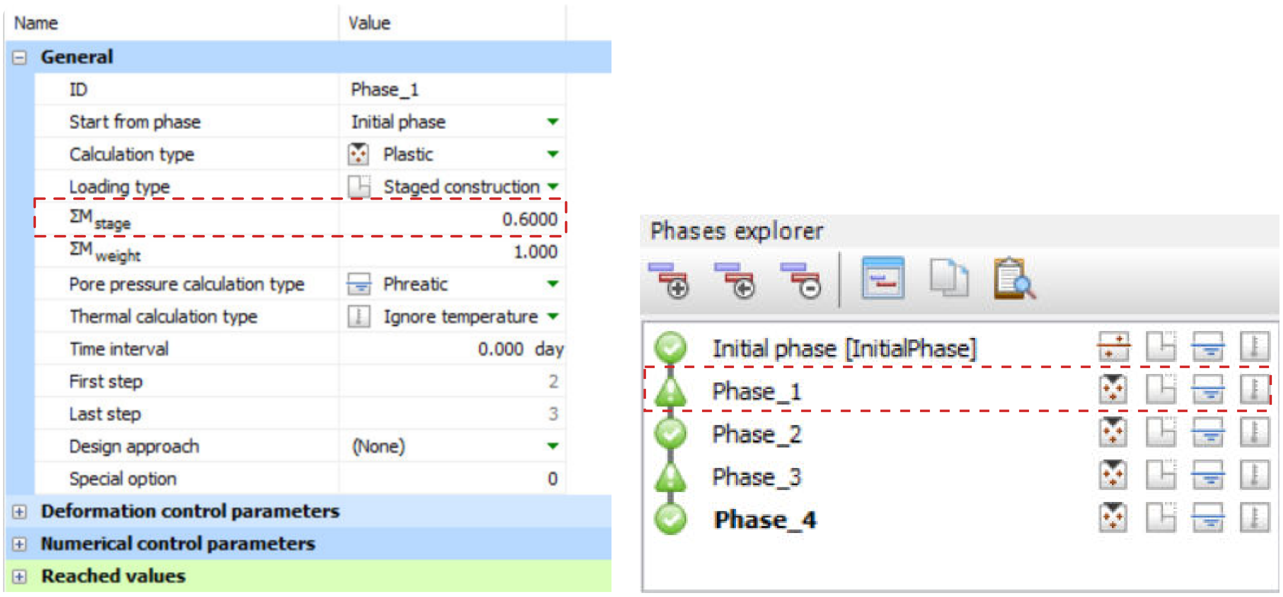
2
Beta-method in PLAXIS 2D

The ***Beta method*** in PLAXIS 2D can be performed using two approaches:

1. *Incomplete Staged construction (SC) method.*
2. *Deconfinement method.*

2.1 Incomplete Staged Construction method

A PLAXIS analysis solves the unbalanced stresses and forces which arises due to the changes defined by the user during the modelling. These unbalanced parameters are then gradually solved during the analysis. In PLAXIS, the *Incomplete Staged Construction* method uses the reduced ultimate level of ΣM_{stage} in the **Staged construction mode** (as displayed in Figure 3 (on page 5)) instead of defining directly a deconfinement value for the deactivated soil clusters . The parameter ΣM_{stage} indicates the amount of unbalance that has been solved during the calculation. In the beginning of the **Staged construction** calculation, when ΣM_{stage} is zero, this force is fully applied to the remaining active mesh, and it will be stepwise decreased to zero with the simultaneous increase of ΣM_{stage} towards unity. In fact, when deactivating the soil clusters, an initial out of balance force occurs that balances the action of the remaining soil, which is initially in equilibrium under a σ_{ini} stress level. It means that at the beginning of the calculation phase, the value of ΣM_{stage} is zero, since no unbalance has been solved yet, however the value of ΣM_{stage} is 1 at the end of calculation phase indicating the unbalanced parameters are solved and the stresses and the forces are in equilibrium again.



a) ΣMstage set to 0.6 in the phases window *b) Unfinished calculation state indication*

Figure 2: Incomplete staged construction

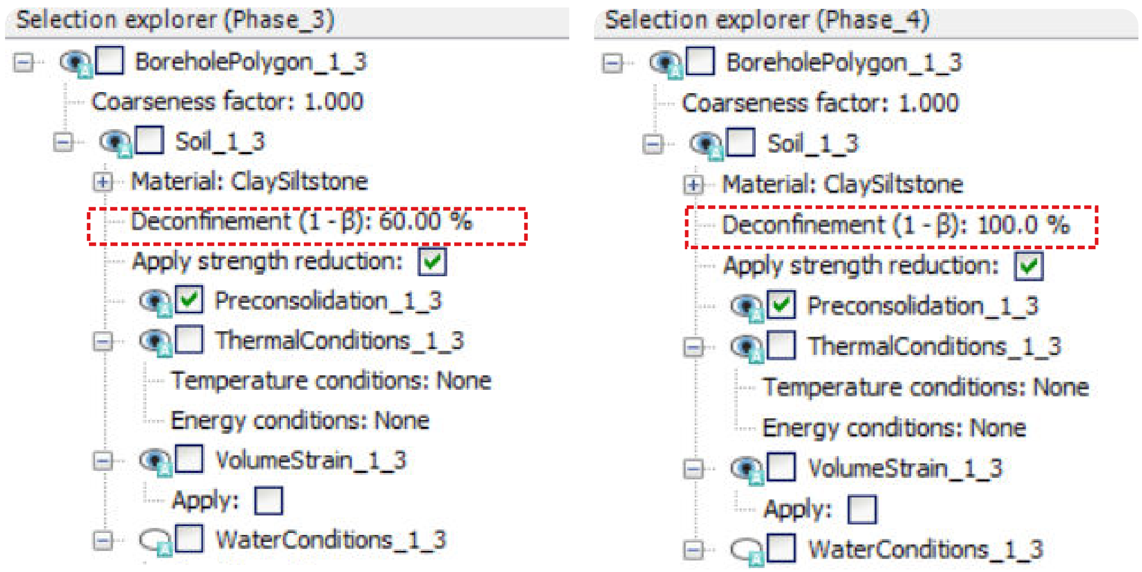
The process of introducing ***Incomplete Staged construction*** in PLAXIS is summarised below:

1. Generate the soil model and define the tunnel using **Tunnel designer** option.
2. De-activate the tunnel clusters without the activation of the tunnel lining and set the ultimate level of ΣM_{stage} with a value equivalent to 1-β.
3. Activate the tunnel lining and make sure the ultimate level of ΣM_{stage} is set to 1 for the last calculation phase.

2.2 Deconfinement method

The *Deconfinement* is defined as the factor $(1 - \beta)$. The aim is that the initial stresses σ_{ini} acting around the location of the tunnel are divided into a $(1 - \beta)\,\sigma_{ini}$ applied to the unsupported part of the tunnel and $\beta\sigma_{ini}$ that is applied in presence of the tunnel lining. To apply this method in PLAXIS 2D, one can use the **Deconfinement** option which is available for each deactivated soil cluster in the **Model explorer** and in the **Selection explorer** respectively. To simulate the construction of the tunnel, a **Staged construction** calculation is needed, in which the tunnel lining is activated and the soil clusters inside the tunnel are deactivated while the *Deconfinement* values are set.

For instance, if 60% of the initial stresses in a de-activated soil cluster needs to be balanced by the unsupported ground in the current calculation phase (hence the remaining 40% needs to be considered later), it means that the *Deconfinement* parameter $(1 - \beta)$ of that inactive cluster should be set to 60% as shown in Figure 2 (on page 6). The value of *Deconfinement* can be increased in subsequent calculation phases until reaching 100% as shown in Figure 2 (on page 6).



a) Deconfinement set to 60% *b) Deconfinement set to 100%*

Figure 3: Deconfinement values in Selection explorer window of PLAXIS 2D

2.3 Difference between Deconfinement and Incomplete Staged construction method in PLAXIS 2D

The main differences between the two methods are listed below:

1. In PLAXIS 2D, with the *Deconfinement* method one can set a (*1-β*) value per tunnel and hence the excavation of multiple tunnels is possible in an independent manner. However, with the *Incomplete Staged construction* method, there is only one global value of (*1-β*), that accounts for the entire model. Therefore, it is possible to have multiple tunnels excavated at the same time with the same excavation sequences.
2. The *Deconfinement method* only considers the change of effective stress and it is not affecting the change of pore pressures which results from changing water conditions or a groundwater flow analysis. However, the *Incomplete Staged construction* method considers change of total stress and hence equally affects both changes of effective stress and pore water pressure.

3 Example for NATM Tunneling using Beta Method

In this chapter an example illustrating the difference between these two methods in dry and wet conditions for an NATM Tunnel problem is described.

3.1 Model definition

An NATM tunnel within a homogeneous soil layer of clay siltstone is modelled. A bore hole was inserted containing the soil layer from 0m to -40m. A material set was created and it was assigned to the bore hole. The parameters of soil considered in this example are mentioned in Table 1 (on page 7). The **Head** is set to 30m in case of wet condition calculation and 0m in case of dry condition calculation. The tunnel is located in the centre of the soil layer.

Table 1: Soil properties

Parameter	Symbol	Clay Siltstone	Unit
General			
Soil model	-	Hoek Brown	-
Drainage type	-	Drained	-
Unsaturated unit weight of soil	γ_{unsat}	25	KN/m^2
Saturated unit weight of soil	γ_{sat}	25	KN/m^2
Mechanical			
Young's modulus	E_{rm}	1.10^6	KN/m^2
Poisson's ratio	ν	0.25	-
Shear modulus	G_{ref}	400.10^3	KN/m^2

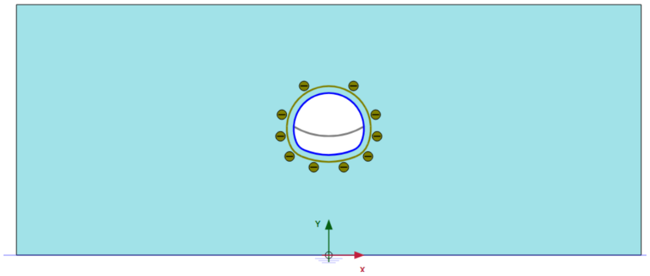
Mechanical			
Uniaxial compressive strength	$\mid \sigma_{ci} \mid$	25.10^3	KN/m^2
Material constant for intact rock	m_i	4	-
Geological strength Index	GSI	60	-
Disturbance factor	D	0.2	-
Dilatancy parameter	ψ_{max}	30	-
Dilatancy parameter	σ_{ψ}	400	KN/m^2
Interfaces			
Strength reduction factor	R_{inter}	0.5	0.5

The parameters for the tunnel lining are shown in Table 2 (on page 8):

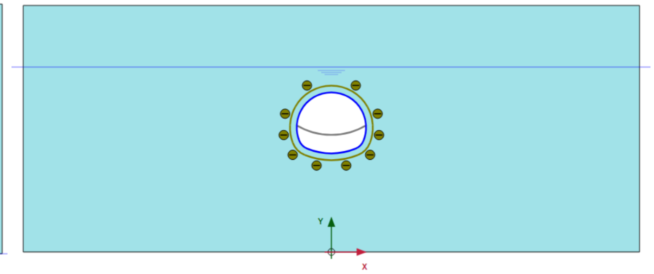
Table 2: Lining properties

Parameter	Symbol	Lining	Unit
General			
Material type	-	Elastic	-
Unit weight	w	5	kN/m/m
Mechanical			
Axial stiffness	EA_1	6.10^6	kN/m
Bending stiffness	EI	20.10^3	$kN/m^2/m$
Poisson's ratio	ν	0.15	-

After defining the soil and lining properties in the **Material Sets** window, then in the **Structures mode**, the tunnel is defined with the help of the **Tunnel designer** (See Figure 4 (on page 9)). Then the mesh is generated, followed by the definition of the model stages.



a) Dry condition



b) Wet condition

Figure 4: Tunnel model in different water conditions

3.2 Defining and performing the calculation in PLAXIS 2D

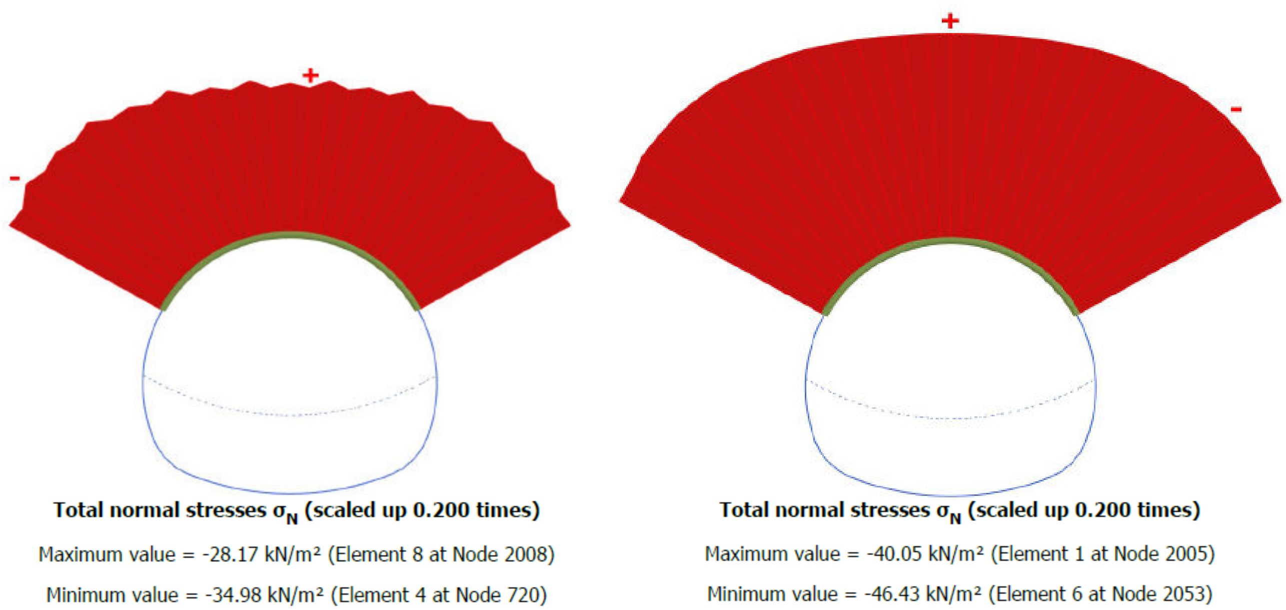
To simulate the construction of the tunnel a **Staged construction** calculation is needed in various phases for both dry and wet conditions. The definition of these phases is described below only for dry condition. For the wet condition the procedure is similar except that the water level is defined at a certain height above the tunnel.

- In **Initial phase**, the soil is excavated, water is not considered for dry case. The phreatic level is considered at the model base and the tunnel is inactive.
- In **Phase-1**, the first part of tunnel is excavated, hence the upper cluster in the tunnel is to be deactivated. While the deactivated cluster is still selected in the **Selection explorer**, the *Deconfinement value* (1-β) was set to the required percentage (i.e., 60% in this example).
- In **Phase-2**, the first temporary lining is activated along with the excavated interfaces from the earlier phases. However, in the **Selection explorer**, the *deconfinement* was set to 100%.
- In **Phase-3**, the lower cluster (invert) is deactivated and in the **Selection explorer**, the *Deconfinement value* of required percentage was set.
- In **Phase-4**, the lining is inserted in the remaining tunnel, so all plates and interfaces around the full tunnel are active. Now selecting the lower cluster, the *deconfinement value* was set to 100%.

For the **Incomplete staged construction method**, the calculation is defined in similar stages for both dry and wet conditions. However, instead of assigning a *Deconfinement value* (1-β) in the clusters, in the **Phases window** for **Phase-1** and **Phase-3** a value for ΣM_{stage} corresponding to (1-β) is set.

3.3 Results

- After running the calculation, it is observed that in the dry conditions when the pore pressures do not change, both the methods gives the same result.
- However, in the wet conditions, when we select the interface stresses in the output, the *Incomplete Staged construction* method gives higher normal stress in the crown of the tunnel than in the *Deconfinement* method as shown in Figure 5 (on page 10).



a)Deconfinement method *b) Incomplete staged construction method*

Figure 5: Resulting interface stresses in wet condition

3.4 Conclusions

The *Deconfinement method* only considers the change of effective stresses and is not applied to the change of pore pressures. As a result, due to the dewatering in the deconfinement phase, the pore pressures will be set to zero. However, in the *Incomplete Staged construction*, the remaining 40% of the unbalanced forces , also leads to remaining 40% of the pore water pressure at the start of the phase. It is summarised schematically by Figure 6 (on page 11).

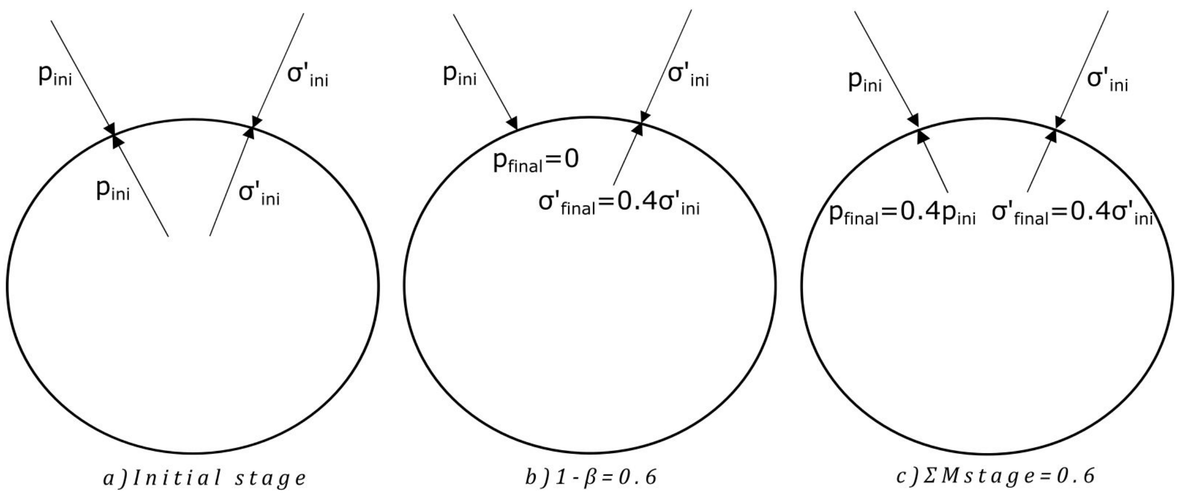


Figure 6: Schematic representation of Deconfinement method vs Incomplete Staged construction method