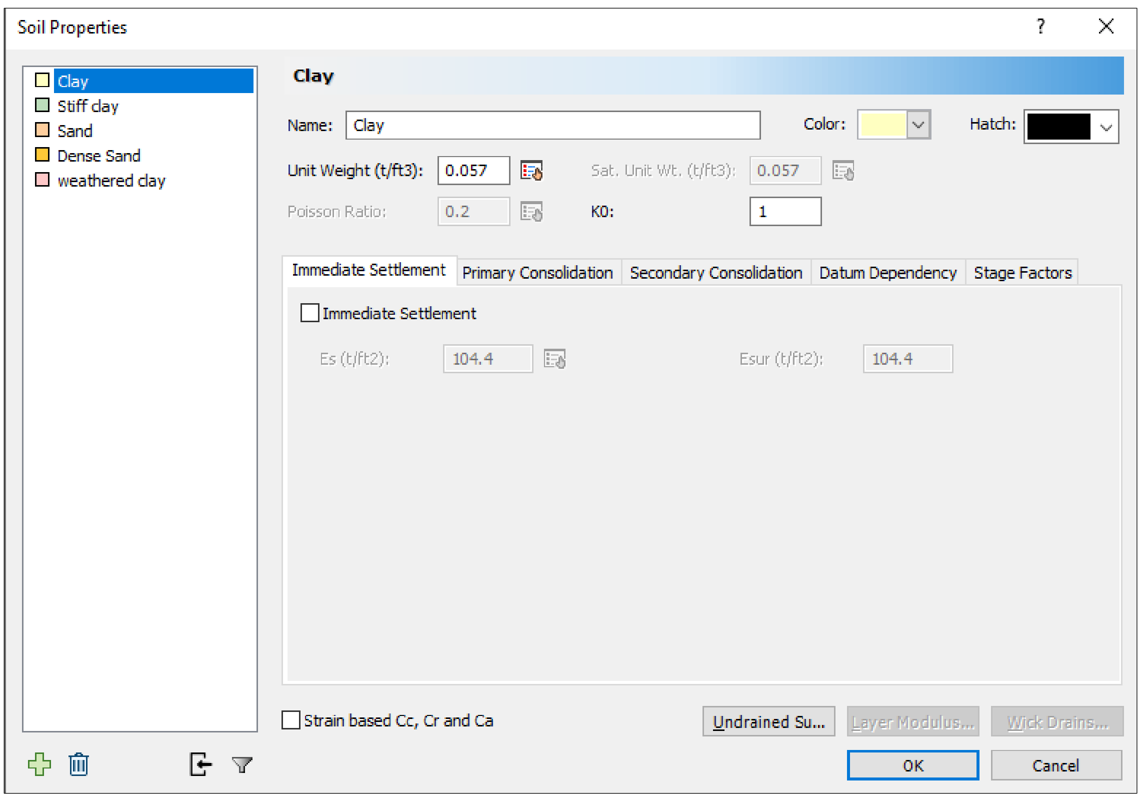
rocscience

ARTICLE

When to Use Immediate Settlement in *Settle3*

Most engineers agree that settlement is made up of three components: immediate, primary consolidation and secondary consolidation (or creep). Most engineers also agree that for specific scenarios, one or two of these components may be missing or negligible. In Settle3, you can turn on or off each of these types of settlement. Users generally know whether their material is creeping, but the question remains, when should you turn on immediate settlement, when should you turn on primary consolidation and when should you turn on both? This article attempts to answer this question through consultation of common texts (see Bibliography) along with users' comments and some of our own insights. We hope that this article will help to 'settle' this matter.



Components of Settlement

Virtually all references agree that the total settlement of a foundation is composed of three components:

$$S_T = S_i + S_c + S_s$$

where:

S_T is the total settlement
S_i is the immediate settlement
S_c is the consolidation or primary settlement
S_s is the secondary settlement or creep

Some of these components may not be present, or the effects may be negligible depending on the soil type. Hence, the ability to turn each component on and off in *Settle3*. But the question remains, when do I use each type of settlement?

Let's make two assumptions:

- The soil grains are incompressible
- Water is incompressible

Neither of these is true of course but the stiffness of the soil grains and the water is generally so large that we can ignore the effects of their compressibility.

With these two assumptions in mind, the only way that settlement can occur is through re-arrangement of the soil grains and/or collapse of pore space. The basic mechanism for settlement is therefore essentially the same for all three types of settlement, and the division into three components is based on other factors.

Secondary Consolidation

Let's first consider secondary consolidation. The secondary settlement, S_s represents time-dependent settlement, or creep, that occurs under a *constant effective stress*. This component of settlement is important in organic soils such as peat but can often be omitted for other soil types. It is easy to separate this component of settlement from the other two since it occurs when effective stress does not change[1]. Therefore we will not discuss this component further.

Immediate Settlement

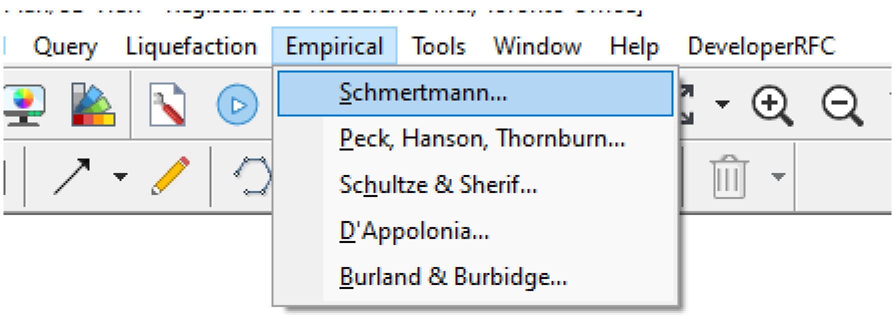
The immediate settlement is also sometimes called *volume distortion* settlement. Essentially, this is the rearrangement of grains due to changing stress, resulting in a reduction in void ratio and instant settlement. In most texts, immediate settlement is considered to be an elastic process. Therefore, the settlement can be calculated from elastic theory (see for example, Day 2005, equation 8.9).

Settle3 also uses elastic theory to calculate immediate settlement. So, by turning on immediate settlement in *Settle3*, you are essentially calculating the volume distortion due to stress changes.

[1] There is research that suggests that creep occurs simultaneously with consolidation settlement, but traditionally, engineers adopt the definition of creep occurring after consolidation settlement. This is the approach adopted by *Settle3.*

One important consideration is that there may be inelastic processes at work (plastic flow), meaning that this immediate settlement calculation will ***underestimate*** the actual settlement. Holtz and Kovaks (1981) state, "The immediate, or distortion, settlement, although not actually elastic is usually estimated by using elastic theory". It is recommended that a lower value of *E* be used to account for the plastic flow.

There are many other methods that try to simplify the elastic calculation, especially in the estimation of *E* from laboratory or field tests. Some of these methods consider the plastic flow, load rigidity and load shape. All are based on empirical settlement data and are therefore grouped under *empirical methods* in *Settle3* (e.g. Schmertmann method). These can also be used to calculate immediate settlement. Note however that these methods are generally not as robust in that they can only consider simple loading geometries. Also, when plotting total settlement, the empirical settlements are not included. You must add them manually.



So when do you need to consider immediate settlement? Immediate settlement is generally assumed to be the settlement that occurs quickly after the construction of your foundation or embankment. How quickly? Bowles (1996) suggests that immediate settlements are those that take place within 7 days of loading. Adopting this definition allows us to consider many possible scenarios that could lead to immediate settlement. These will be discussed in the next section.

Primary Consolidation

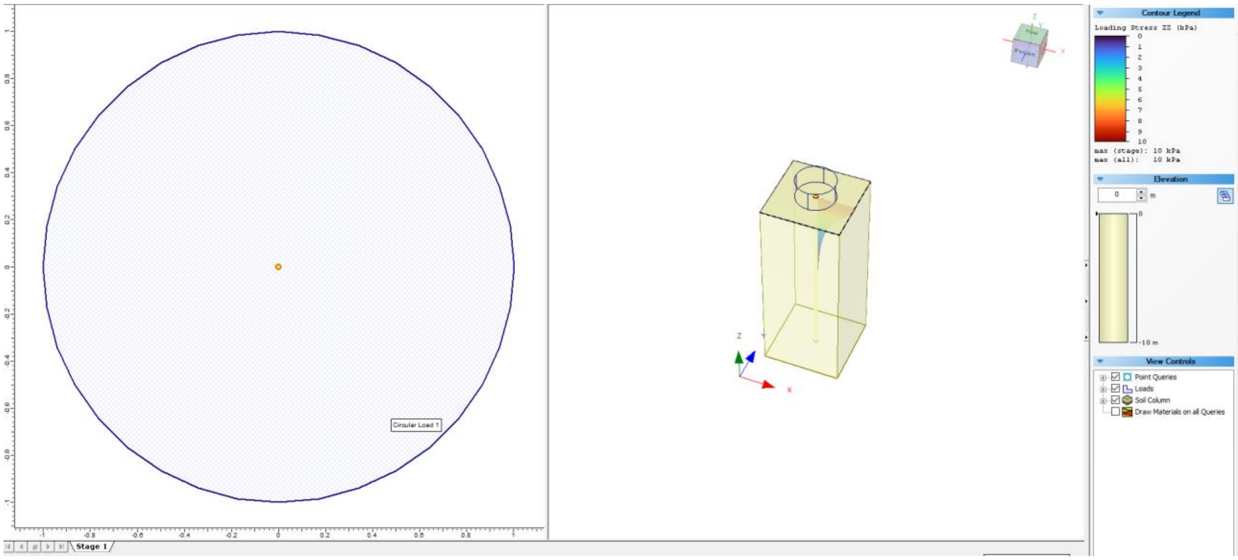
The primary consolidation settlement, S_c is the gradual re-arrangement of grains as water is expelled. This component of settlement is usually dominant in finegrained saturated clays. But consolidation also occurs in other soil types. Hence, there is some gray area as to when to use immediate settlement, when to use primary consolidation settlement and when to use both. The following section outlines different possible scenarios and how to simulate them in *Settle3*.

Settlement Scenarios

In this section, we consider different settlement scenarios and how to deal with them in *Settle3*. First we will describe a simple test model used to illustrate each situation.

Test Model

Consider a flexible circular load of magnitude q = 10 kPa and radius a = 1 m on top of a soil layer with thickness h = 10 m. We will use this model to examine different scenarios. Looking at the screen capture below, a query point is placed at the centre of the circle for calculation of settlements.

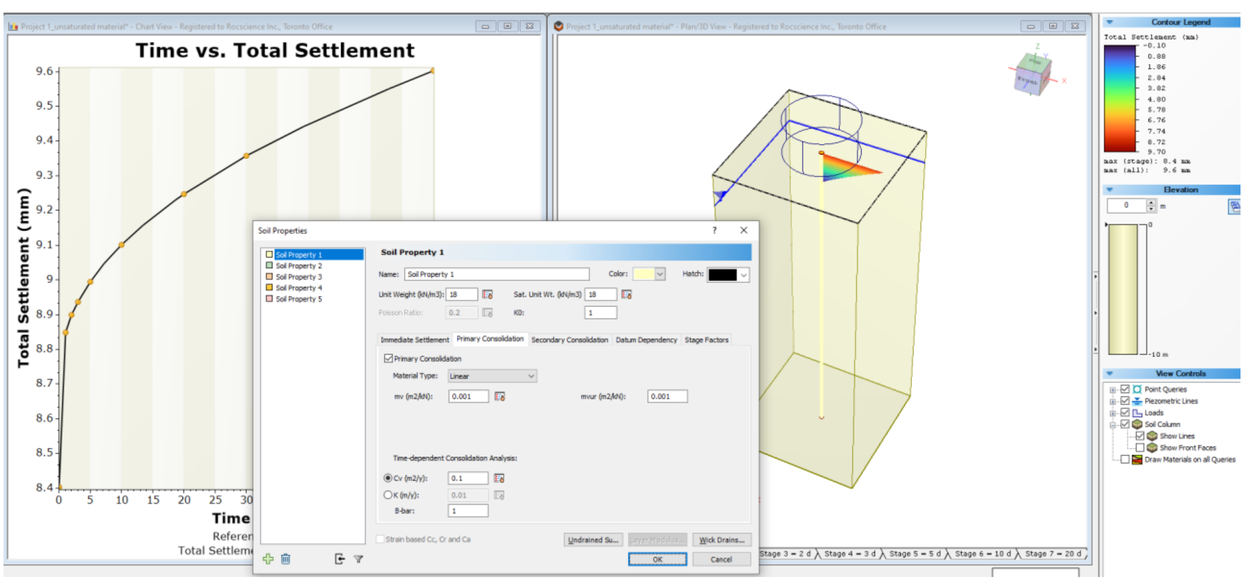


Scenario 1: Unsaturated Material

In this case, there is no consolidation and all of the settlement is immediate. However, this doesn't necessarily mean that you should turn on immediate settlement and turn off consolidation settlement. If you turn on consolidation settlement for an unsaturated material, then the settlement will occur 'immediately' since there is no time-dependent dissipation of pore pressures.

This technique would be useful in two possible scenarios:

- Your material layer is partially below the water table. In this case, you can turn on consolidation settlement and turn off immediate settlement. The soil that is above the water table will compact immediately and the soil below the water table will compact gradually.
- Your material is non-linear and you wish to use the non-linear parameters C_c and C_r. In this case, you must use consolidation settlement and not immediate settlement.

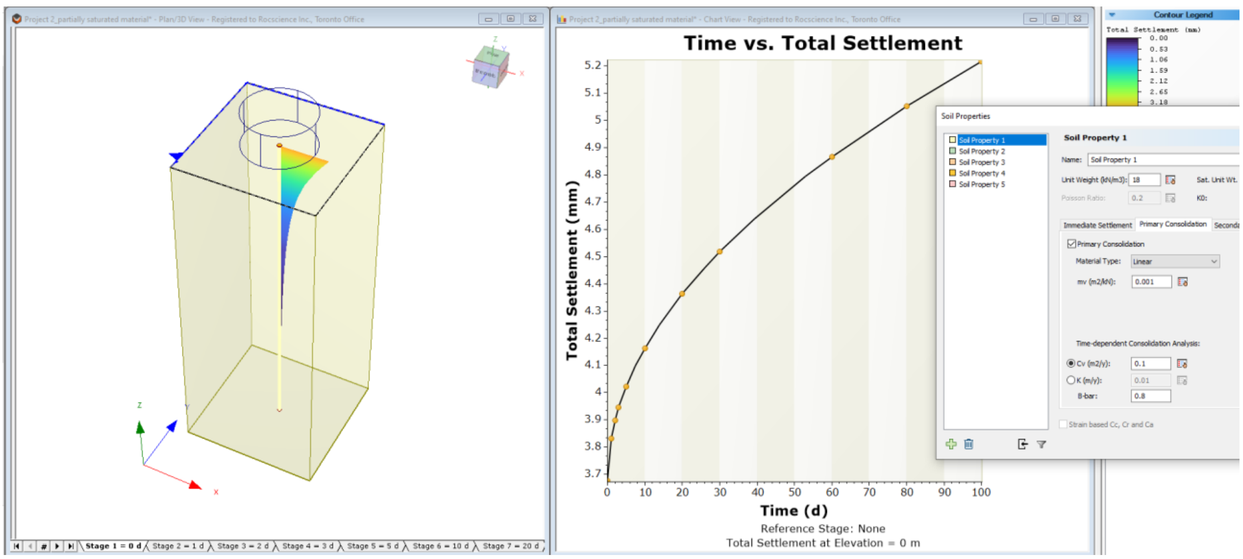


For the unsaturated material, it doesn't matter if you choose immediate or consolidation settlement, as long as you don't choose both.

In fact, if you choose consolidation settlement with a linear material, m_v is just the inverse of *E* that is used for immediate settlement. So a model with m_v = 0.001 m^2/kN will give exactly the same settlement as a model with *E* = 1000 kPa.

Scenario 2: Partially Saturated Material

In this case there will be some immediate settlement as air is quickly pushed out of the pore spaces. However, as with the unsaturated case, it is not necessary to turn on immediate settlement. In *Settle3*, you can account for this effect by setting the B-bar less than 1 (B-bar ranges from 0 for an unsaturated material to 1 for a saturated material - see the Theory manual for more details). When you do this, a proportion of the applied stress is transferred immediately to the soil so that you see some immediate deformation.

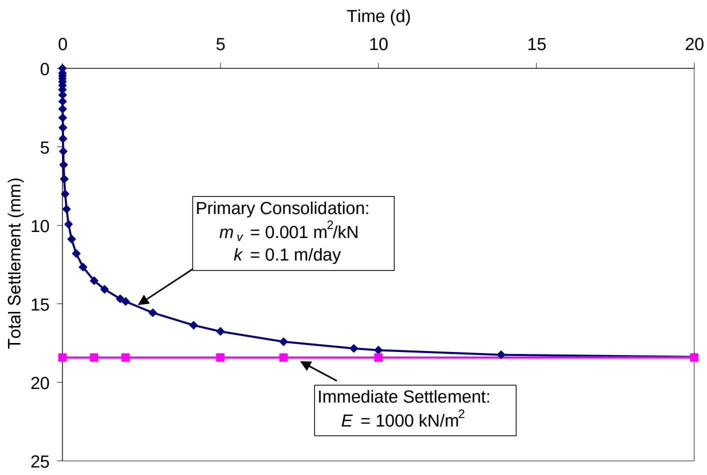


Scenario 3: Fully Saturated Sand

If you are dealing with sand, or some other coarse grained material that has a high permeability, then pore pressures dissipate quickly and settlement is essentially immediate. In *Settle3*, you can simulate this in several ways:

- Turn on Immediate Settlement and turn off Primary Consolidation
- Turn off Immediate Settlement, turn on Primary Consolidation and set a large value for c_v or *k*.
- Turn off both Immediate Settlement and Primary Consolidation and use one of the Empirical Methods.

The figure on the following page shows a comparison of results for the first method and the second method.



Comparison of settlement results for the circular load model using different methods to account for rapid pore pressure dissipation.

Scenario 4: Fully Saturated Clay

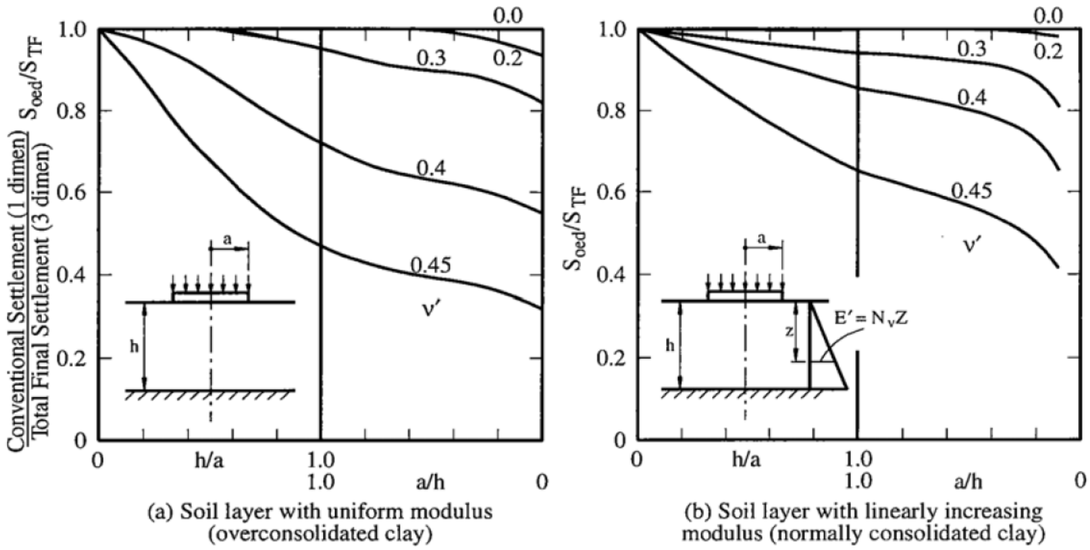
This is probably the only situation in which you *may* want to use both Immediate Settlement and Primary Consolidation. *Settle3* uses one-dimensional consolidation theory to calculate the Primary Consolidation settlement. However, most loading scenarios are actually three-dimensional. Therefore even with an incompressible fluid, some volume distortion settlement will occur immediately in a saturated clay.

Elastic theory can be used to estimate this settlement with one important consideration: you should use the ***undrained*** Young's modulus and Poisson's ratio. The undrained Poisson's ratio is 0.5 (a lower number can be used if not 100% saturated). The undrained Young's modulus can be calculated by:

$$E_{undrained} = \frac{3E_{drained}}{2(1+\nu_{drained})}$$

so, for a material with a Poisson's ratio of 0.2, $E_{undrained}$ = 1.25$E_{drained}$. However, Lambe and Whitman (1979) state that "With actual soils, the ratio of $E_{undrained}/E_{drained}$ is typically much larger than this theoretical value. Values of 3 or 4 are not uncommon for normally consolidated clays."

It is also important to note that this is a three-dimensional effect, so the amount of immediate settlement depends on the geometry of the situation and the drained Poisson's ratio. For a load with very large areal extent, or low $\nu_{drained}$ the situation is close to a one-dimensional loading scenario, so the immediate settlement will be negligible. Poulos (2000) presents graphs showing the importance of these parameters in calculation of immediate settlement.

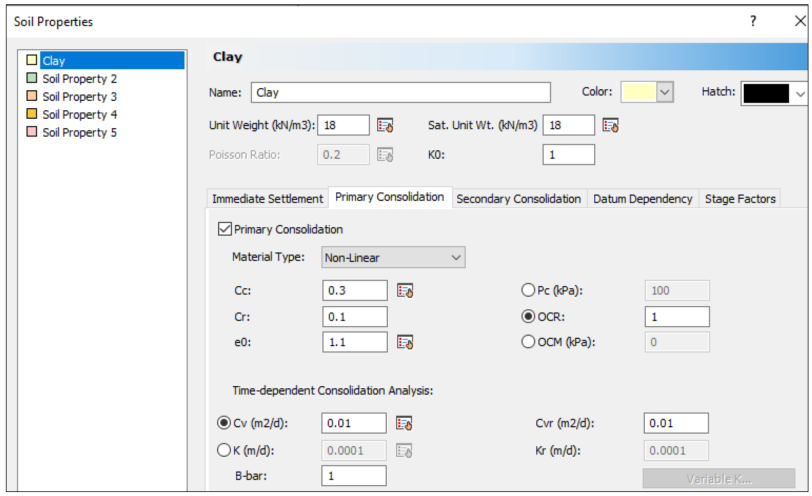


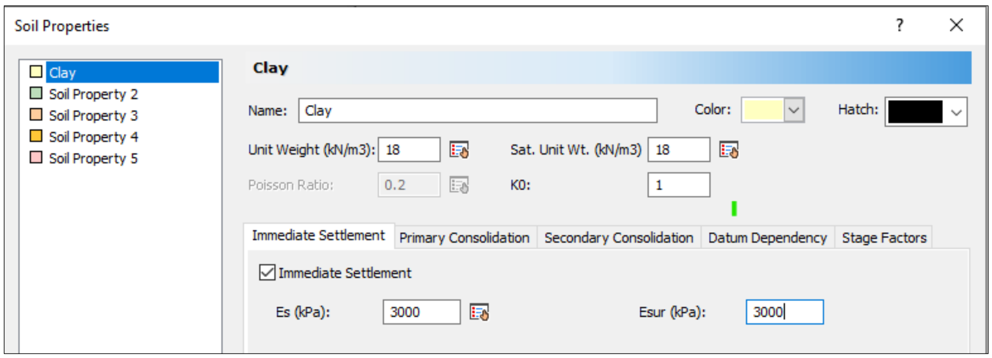
Theoretical ability of one-dimensional (Primary Consolidation) analysis to predict total final settlement. From Poulos (2000).

For soft, normally consolidated materials, Immediate Settlement should be added to the Primary Consolidation settlement. Therefore, the following equation applies:

$S_T = S_i + S_C$ Soft, normally consolidated clays

However Poulos (and others) suggest that for normally consolidated clays, the immediate settlement as a proportion of the total settlement is often negligible. This is illustrated on the following page.

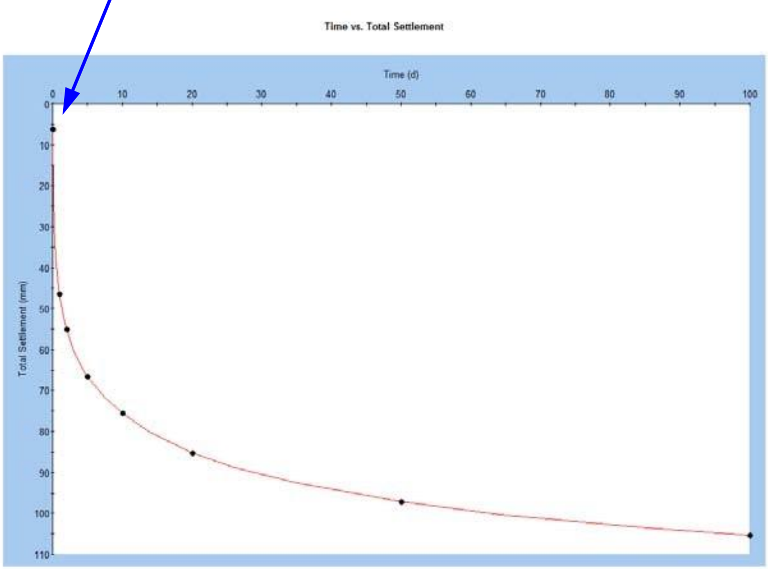




<u>Normally consolidated clay:</u>

$E_{undrained} \sim 3 \times E_{drained}$

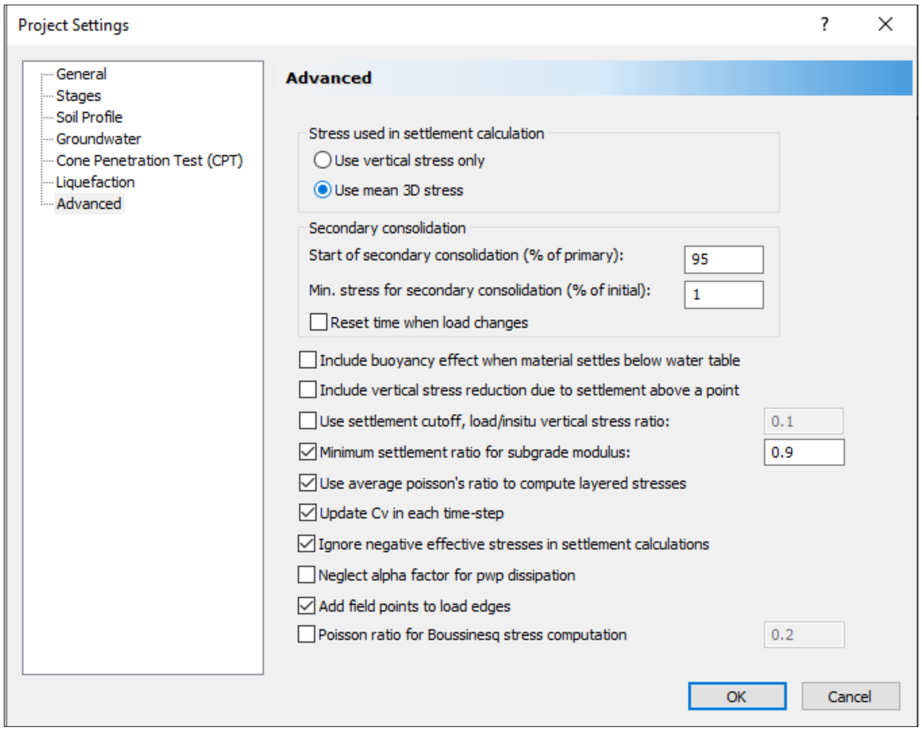
S_i is small



For stiff overconsolidated material, Poulos warns that the immediate settlement should not necessarily be added to the Primary Consolidation settlement. Instead the immediate settlement accounts for part of the Primary Consolidation

Settlement and that if you add them together, you will be 'double-counting'. In *Settle3* therefore, you would have to somehow reduce the calculated consolidation settlement to balance the immediate settlement.

In *Settle3*, these three-dimensional effects can be more easily accounted for in another way. Go to Project Settings, choose the Advanced tab and select Use Mean 3D Stress as shown:

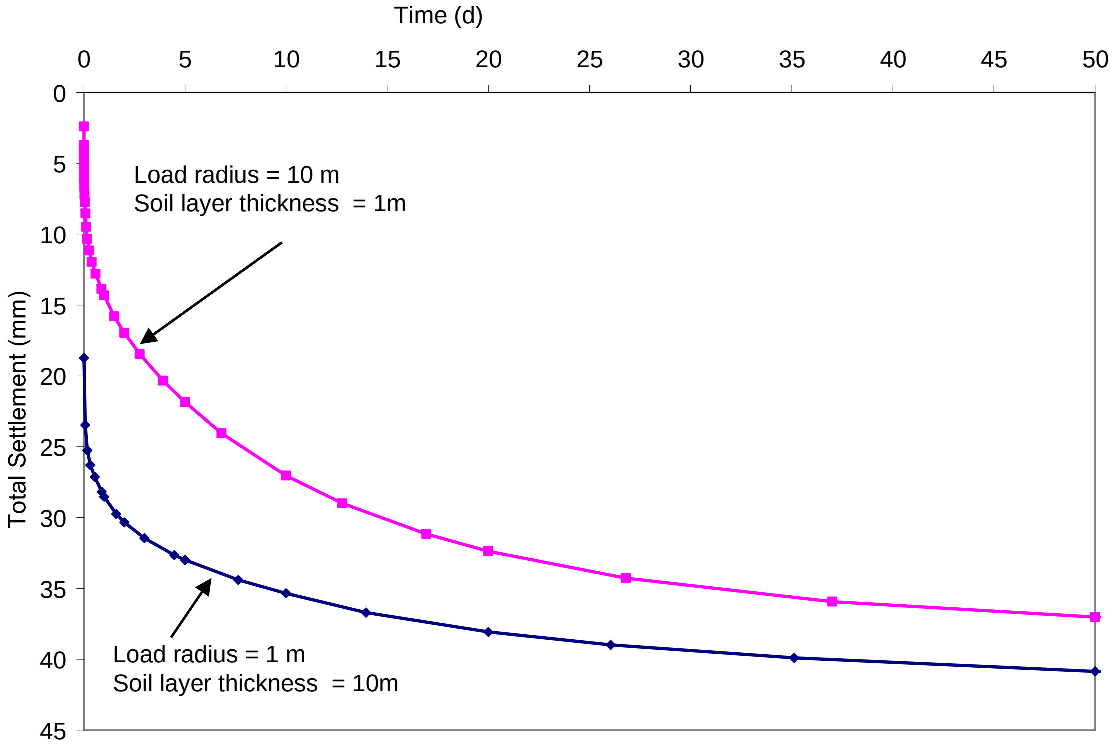


Settle3 will now set the initial excess pore pressure to be equal to the undrained mean stress rather than the vertical stress, where the undrained mean stress is:

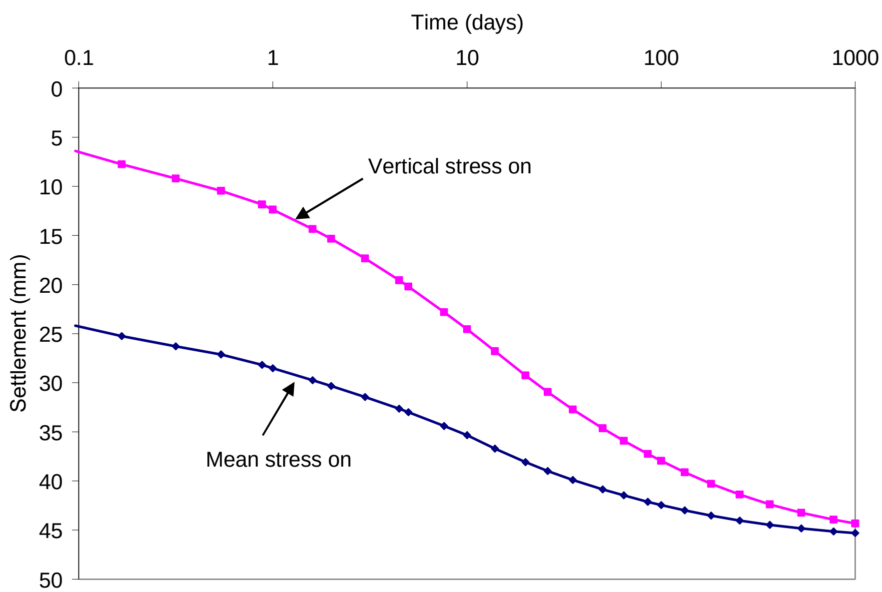
$$\sigma_M^{undrained} = \frac{1}{3}\left(\sigma_1 + \sigma_2 + \sigma_3\right)_{\nu=0.5}$$

See the Theory Manual, section 4.2 and Das (2007) for details. Using the mean stress instead of the vertical stress means that when a load is applied, part of the load is instantly carried by the grain skeleton. This results in some immediate settlement. Since the calculated mean stress is a function of the load geometry, there is no need to apply a fudge factor to account for the size of the load. The plot below shows how immediate settlement is significant for a small load on a thick layer, yet insignificant for a large load on a thin layer.

The subsequent plot also shows how a model that does not have mean stress turned on produces the same long-term settlement as the model with mean stress turned on. This shows how the immediate settlement is not being 'doublecounted' when mean stress is turned on.



Settlement calculated for overconsolidated clay with mean stress option turned on.



Settlement calculated for the 10 m load with mean stress turned on compared to the settlement calculated with vertical stress only.

Summary

The table below summarizes how to model different scenarios in *Settle3*. This is only a guideline and specific sites, loading scenarios and acquired data may demand a different approach for your settlement problem. As always, you should use your engineering judgment when creating and analyzing these numerical models.

Material	Possible Methods
Unsaturated	1. Immediate on*, primary off *or* 2. Immediate off, primary on
Partially saturated	1. Immediate off, primary on with B-bar < 1
Sand	1. Immediate on*, primary off *or* 2. Immediate off, primary on, c_v or *k* is large *or* 3. Immediate and primary off, use empirical method
Saturated normally consolidated clay	1. Primary on + (optional) immediate on* with undrained parameters**
Saturated overconsolidated clay	1. Primary on, immediate off, mean stress on *or* 2. Immediate on* with undrained parameters** + primary on + correction to account for double-counting

* Elastic solutions do not account for plastic flow and may therefore underestimate the actual settlement

** Undrained stiffness parameters calculated from theory may be too soft, therefore the immediate settlement may be overestimated

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