# ZSWalls+R™

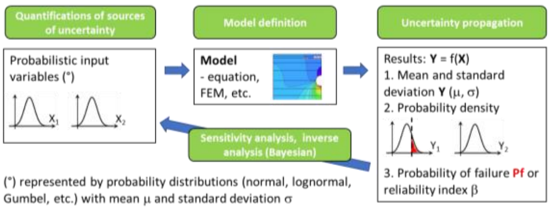
## Mastering uncertainties in deep excavations calculations

### Probabilistic analyses

The input parameters of calculation models in civil engineering are marred by uncertainties. In geotechnics in particular, soil strength and deformation parameters are defined on the basis of a small number of boreholes. The level of the water table and load values are also uncertain.

Conventional (or deterministic) approaches, documented in the standards and norms, recommend the use of global or partial safety factors to define conservative parameters in order to design structures such as foundations, retaining walls, tunnels, slopes and embankments. Within this deterministic framework, the quantification of risk is very difficult (not to say impossible), since its commonly accepted definition encompasses the notions of danger, severity, acceptability, and depends mainly directly on the probability of occurrence of a failure.

Probabilistic approaches make it possible to take into account these uncertainties and define the input parameters of our models not in a deterministic way, but rather with the help of statistical distributions. The results (forces, displacements, safety factors) will therefore also be probabilistic, the uncertainties being propagated through our calculation model.




### ZSWalls+R™ = ZSWalls™ + Reliability

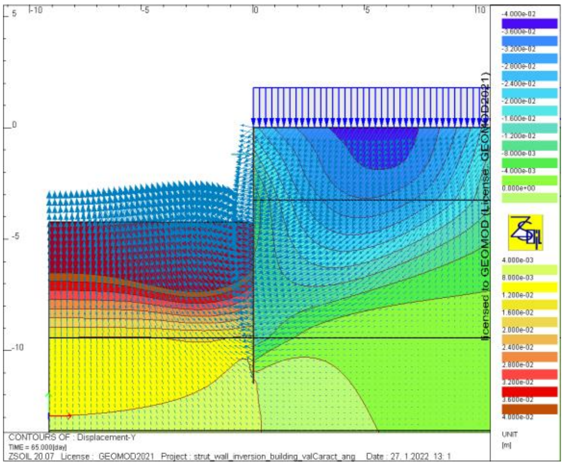
ZSWalls+R™ embeds all these concepts via www.uqlab.com in order to apply it to ZSWalls™, a 2D deep excavation - retaining wall analysis software program. The program is based on the finite element method including coupled formulation for fully- and partially saturated two-phase media and advanced constitutive laws.

ZSWalls™ offers a user-friendly graphical interface, simplifed overall input strategy, automated and user-configured, ready to print reporting, a variety of support elements which can be associated with different excavation methods like: retaining walls (diaphragm or sheet-pile), tiebacks - anchors, nails, internal bracing - struts, top/down technique - slabs.

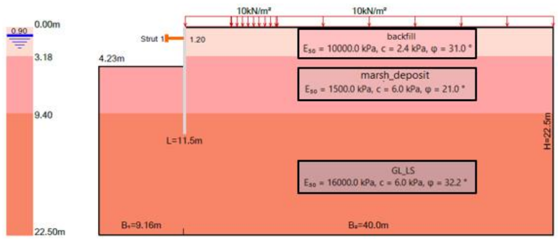
### Sheet-pile wall example

A 4.2 meters deep excavation has to be constructed in relatively bad soil conditions, consisting of a backfill and marsh deposits. The water table lies close to the soil subsurface. A sheet-pile wall has been predesigned, with one level of bracing, 1.20 m below the sheet-pile's head.

An existing silo stands 5 to 10 meters behind the excavation. According to the engineers, the settlement of this silo has to remain smaller than 3.5 cm. A first deterministic computation with ZSOIL® yields a 4.0 cm settlement.

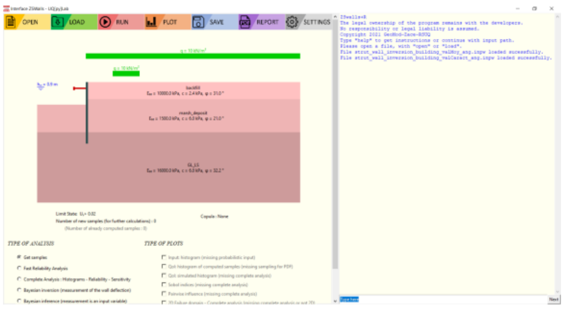


The same settlement can be obtained with ZSWalls™, in a matter of minutes, thanks to the simplified input definition screen.



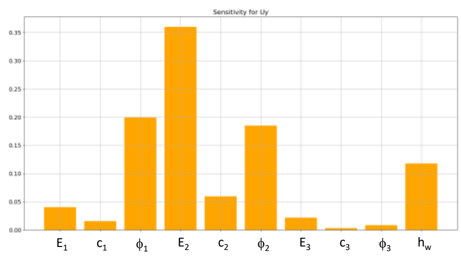

Within the deterministic framework, it is hard to define the probability that the settlement of the silo will actually exceed 3.5 cm, given that the deterministic approach with characteristic soil values gives us a settlement of 4.0 cm.

Now, within ZSWalls+R™, it is possible to specify probability density functions (given by (log)normal, Beta, Uniform or Gumbel distributions with means and standard deviations) for the Young's modulus, the friction angle and the cohesion of every soil, as well as the water table height and the surface loads. Then, a real probabilistic analysis will be possible, propagating the input variables' uncertainties across ZSWalls™, in order to get probabilistic results such as safety factors, horizontal or vertical displacements and bending moments.



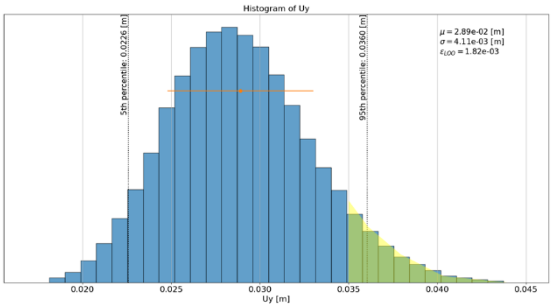
| | Variables | Deterministic | Mean | Standard deviation | CoV |
|---|---|---|---|---|---|
| backfill | E | 10000 | 10000 | 2000 | 20% |
| | c | 2,4 | 3,4 | 0,68 | 20% |
| | ϕ | 31 | 36,7 | 3,7 | 10% |
| Marsh deposit | E | 1500 | 1500 | 300 | 20% |
| | c | 6 | 8,5 | 1,7 | 20% |
| | ϕ | 21 | 24,8 | 2,5 | 10% |
| GL_LS | E | 16000 | 16000 | 3200 | 20% |
| | c | 6 | 8,5 | 1,7 | 20% |
| | ϕ | 32,2 | 38,1 | 3,8 | 10% |
| | $h_w$ | 0,9 | 0,9 | 0,09 | 10% |

**Sensitivity analyses** provide a better understanding of the problem, since they make it possible to determine the most influential input variables on the results (displacements, bending moments, safety) and therefore allow to concentrate on the most important parameters. Observe here that $\phi_1$, $E_2$ and $\phi_2$ are the most significant parameters for the evaluation of the settlement.




In ultimate state analyses, **reliability analyses** help determine the probability of failure Pf of a structure as the integral below the probability density function of the safety factor FS, when FS < 1. By analogy, it is also possible to calculate the probability of failure of a system at the serviceability limit state as the integral under the probability density of a displacement d, when d > d(limit).

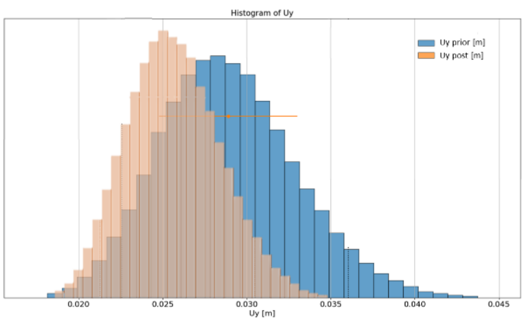
Looking at the settlement histogram yields Pf(settlement > 3.5 cm) = 7.6%.




Correlations can be also taken into account. Here, introducing a negative correlation of -0.8 between c and ϕ yields a new Pf(settlement > 3.5 cm) = 5.2%.

The uncertainties about the result (here a settlement), quantified by the notion of standard deviation, depend greatly on the uncertainties present in the input parameters of the model. It is therefore essential to reduce these uncertainties. For this, two possibilities: multiply the in situ and laboratory tests on soil samples, or use experience and in situ measurements (displacements during execution, water levels, ...) in order to update our calculation hypotheses. The first possibility is always possible, but can be expensive. In addition, the new surveys will not give us an indication of the real value of the solicitations involved (loads, water level, etc.). The use of **Bayesian inference**, or inverse analysis, makes it possible to formalize the second possibility with a coherent and generic methodology, in order to refine the measurement of the probability of failure (from a priori to a posteriori), then optimize the design and save money and $CO_2$ if the value of Pf decreases a posteriori.

Here a 1.5 cm horizontal displacement is measured 1 m below the soil's surface, when the excavation has reached 1.9 m. ZSWalls+R allows you to update the probability that the silo's settlement will exceed 35 mm, given the new information that we have at hand. Observe that, in our case, Pf reduces drastically and ends being smaller than 0.1 %.




Lausanne, February 2022