Smart JetPlug: User Manual

1. What is Smart JetPlug?

Smart JetPlug is a software conceived for designing jet grouted bottom plugs (i.e. bottom plugs obtained by partial overlapping of jet grouted columns) with reference to static and hydraulic limit states. In the following, indications are given on how to use the code. For a deeper understanding of the adopted approaches, refer to the references listed at the end of this document.
The software considers for the plug the geometrical scheme depicted in Figure 1, in which h_p, h_s and h_{jg} are respectively the total height of the plug, the height of the part intentionally left untreated, and the height of the jet grouted part. By posing h_s=0, a fully treated plug is considered.

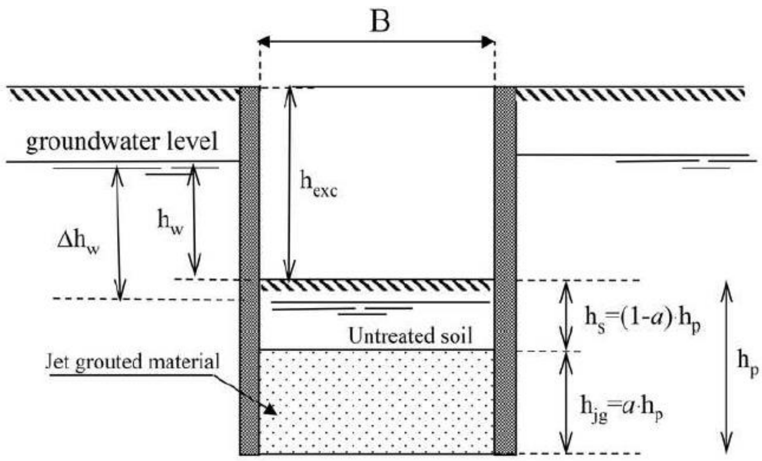


Figure 1. Geometrical scheme of a bottom plug, with a treated (h_{jg}) and an untreated (h_s) part.

2. How does Smart JetPlug work?

Smart JetPlug uses a probabilistic approach to consider the random variability of grouted columns position (axis deviation), diameter and strength, and allows calculations with any possible number of columns with any desired spacing, with the only constraint of considering only jet plugs having a rectangular area. More complex configurations can be analysed by dividing them in rectangular sub-areas.
The code is composed of three subsequent sections:

- ***Static Calculation***: in this section the height of the bottom plug is calculated on the bases of equilibrium considerations.
- ***Grid Generation***: in this section the geometrical layout of the columns is assigned.
- ***Water Flow Calculation***: in this section the water flow through the untreated portion of the jet grouted part of the plug is calculated. This water flow depends on the possible lack of mutual overlapping among the columns, which depends on the chosen layout and on the random variability of columns' position and diameter.

3. Starting Smart JetPlug

The software can be downloaded from the Smart-G website (www.smart-g.eu) following the registration procedure. The download package includes the .exe file necessary to install the program on the local device. Each time the software is used, the initial screen requires the email address used during registration and the associated license key. The code can be used once an authorized e-mail address and the corresponding licence key are texted in the start window (Figure 2).
Once both the email address and the license key are verified, the software is ready for a run.

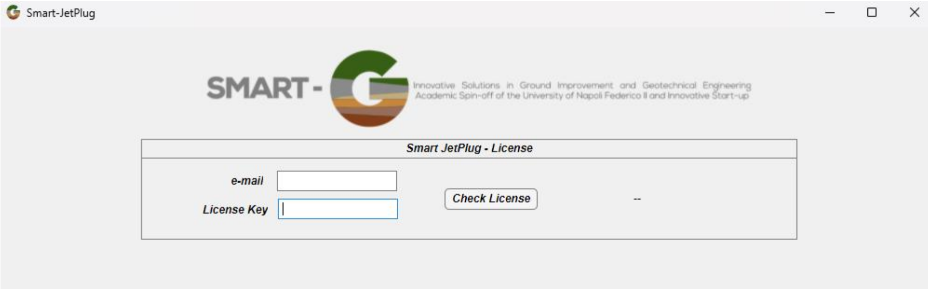


Figure 2. Smart JetPlug start screen.

4. Static calculation

In this section, the program calculates the minimum plug thickness necessary to guarantee the equilibrium of the structure, with reference to possible uplift and bending failure mechanisms caused by the hydraulic pressure acting on the bottom of the plug. Two values of h_{jg} are calculated with reference to these two mechanisms,

Mechanism 1: uplift failure

The uplift failure mechanism is depicted in Figure 3, and considers two possible cases: no shear resistance to the uplift mechanism on the lateral surface of the plug (extremely conservative design choice), or the attainment of the shear strength at the interface between the retaining structure and the jet grouted part of the bottom plug. In neither case the shear strength of the untreated part of the plug (h_s) is considered.

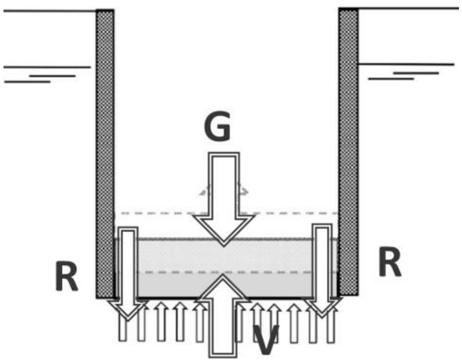


Figure 3. Uplift failure mechanism.

Following the notations introduced by Eurocodes, the equation governing uplift equilibrium is:

$$\frac{1}{\gamma_R} \cdot R_d \left(\frac{M_{i_k}}{\gamma_{Mi}} \right) = \gamma_v \cdot V_k - \gamma_G \cdot G_k \tag{1}$$

where:

- R_d is the stabilising action due to the shear stresses acting on the lateral surface of the jet grouted part of the plug. If this contribution is neglected, R_d=0.
- V_k is the resulting water uplift destabilising action on the plug.
- G_k is the stabilising action (sum of the weight of the treated and untreated parts of soil)
- M_{ik} are the characteristic value of material property. In this case, the shear strength should be considered through the shear strength angle φ' and the effective cohesion c' at the interface between the retaining structure and the plug. Following the indication by Modoni et al. (2016), the shear strength is herein set as a fraction δ of the unconfined compressive strength $q_{u,jg}$ of the jet grouted material (i.e. $M_{ik}=\delta \cdot q_{u,jg}$). The parameter δ depends on the shear strength angle φ' of the jet grouted material.
- γ_{Mi}, γ_V and γ_G are partial factor for soil parameter, permanent stabilising action and permanent destabilising action respectively. In this case, the partial factor on the strength parameters is $\gamma_{Mi}=\gamma_{qu}$.
- γ_R is the partial factor for the resistance. The default value of γ_R is 1, but different values can be chosen by the user.

With reference to the geometrical scheme depicted in Figure 1, eq. (1) is solved to define the minimum height h_{jg} of the jet grouted part of the bottom plug needed to guaranteed the equilibrium with reference to vertical translation ($h_{jg,uplift}$).

Mechanism 2: bending failure

The minimum height of the jet grouted bottom plug is also calculated with reference to the bending failure mechanism schematically represented in Figure 4, and named $h_{jg,bending}$. The equilibrium to rotation is solved for one of the two blocks in which the plug is devided by the depicted failure mechanism, as reported in the figure. Partial factors are considered as for the uplift mechanism.

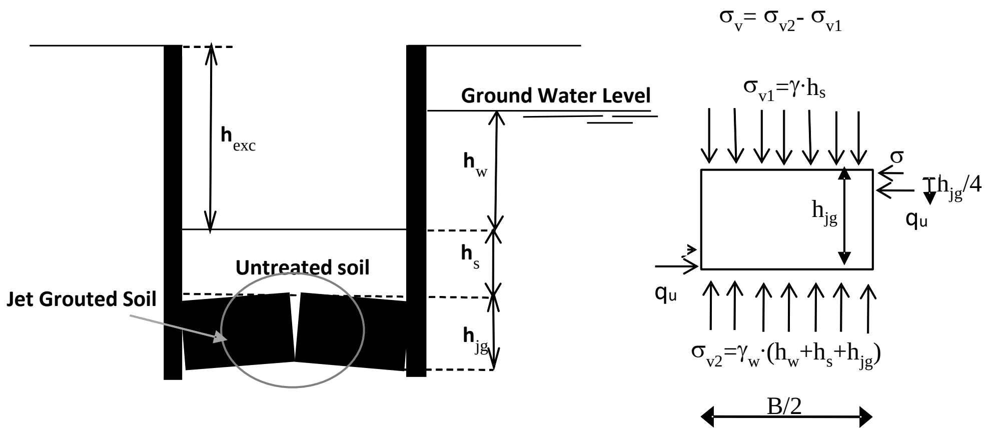


Figure 4. Bending failure mechanism.

The operator has therefore two possible values of h_{jg} (respectively $h_{jg,uplift}$, and $h_{jg,bending}$). The code reports these two values along with the suggested value $h_{jg,min}$ (which is the highest between the two).

The input screen of the static calculation section is reported in Figure 5. The input data are divided in three categories: ***Geometric, Soil&Jet*** and ***Statistic Parameters***.
In the ***Geometric Parameters*** panel, the input properties are referred to the geometrical scheme reported in Figure 1.

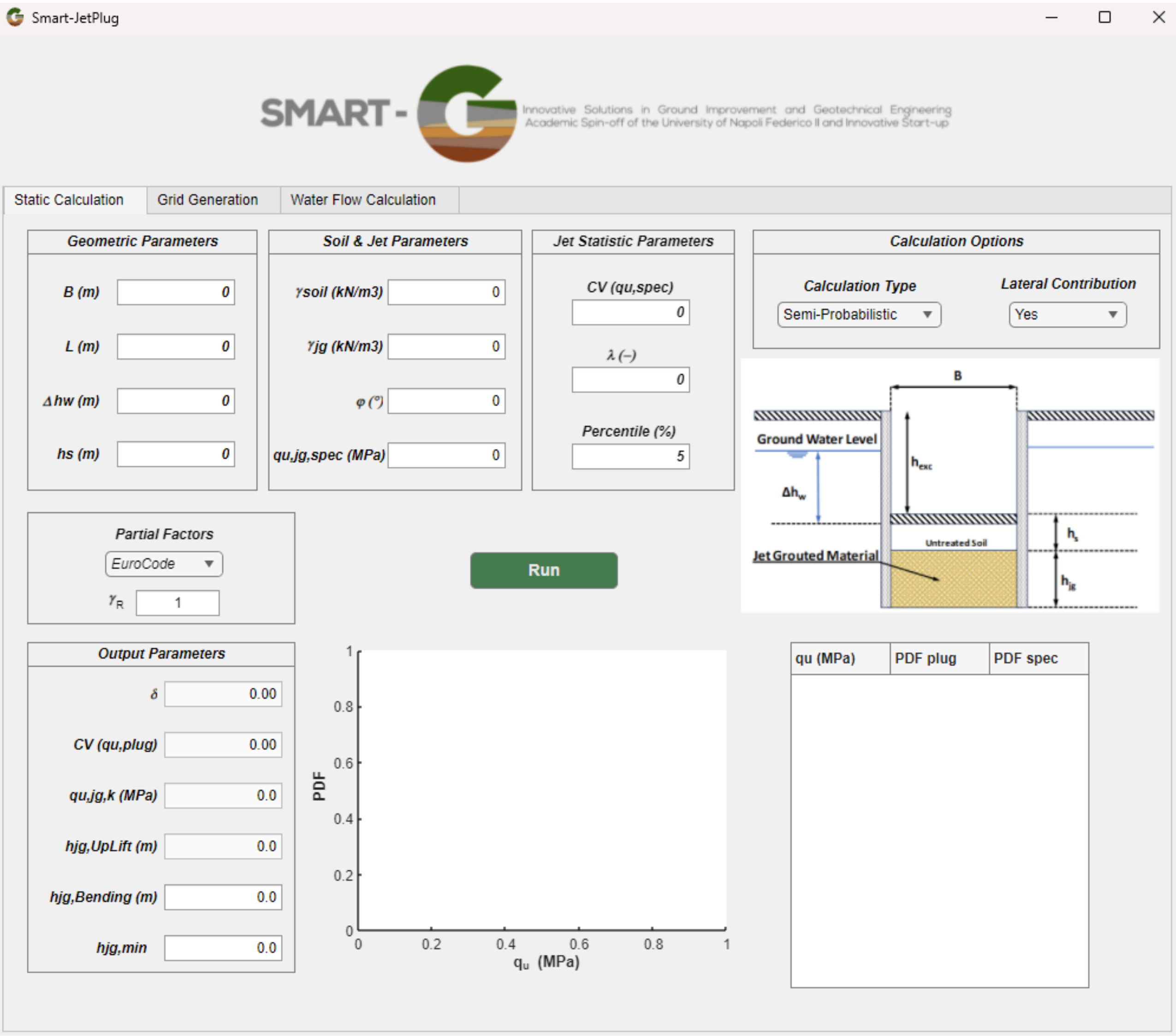


Figure 5. Input screen.

In the ***Soil & Jet Parameters*** panel, the following input data are requested:

- γ_{soil}: unit weight of the untreated soil, needed if $h_s \neq 0$ (kN/m^3).
- γ_{jg}: unit weight of the jet grouted column (kN/m^3).
- φ': shear strength angle of the jet grouted material (°).
- $q_{u,jg,spec}$: average uniaxial compressive strength of the treated soil (MPa) at the specimens' scale.

The compressive strength $q_{u,ig}$ of the jet grouted material is considered to have a lognormal probabilistic distribution. Therefore, parameters must be assigned for it in the ***Jet Statistic Parameters*** panel:

- CV($q_{u,jg,spec}$): coefficient of variation of the uniaxial compressive strength, related to the behaviour at the specimens' scale.
- λ: empirical parameter (<1) introduced to take into account that the overall variability of $q_{u,jg}$ (named $q_{u,jg,plug}$) is smaller than that at the specimens' scale. Therefore CV($q_{u,jg,plug}$)=λ·CV($q_{u,jg,specimens}$). Typically, 0.4≤ λ ≤0.55 for bottom plugs and λ≈0.7 for isolated columns.
- Percentile p_r (%): for the considered distribution, it defines the value of qu,jg,plug on the lognormal distribution that will be used in the deterministic equilibrium calculations. In the software, the default value is 5%, but any value can be set by the operator.

Finally, in the ***Calculation Options*** panel the following options can be set:

- Calculation Type: (*Semi-Probabilistic/Deterministic*). This option allows to apply or not the statistical correction on the average uniaxial compressive strength of the treated soil at the specimens' scale (if Deterministic is selected $q_{u,jg,spec}$:= $q_{u,jg,plug}$ =$q_{u,jg,k}$)
- Consider lateral shear strength? (*yes/no*). This option allows to consider or not the positive contribution of the lateral shear strength in the calculation of $h_{jg,uplift}$.

When all the needed input variables and parameters have been assigned, the ***Run*** button must be clicked. In the *Output Parameters* panel, the following output data are displayed:

- δ: φ-dependent parameter used to calculate the shear strength at the interface between the retaining structure and the jet grouted part of the plug (the shear strength of the untreated part is neglected in the calculation). In case the option of no contribution of the lateral shear strength has been chosen, this value is automatically set equal to zero.
- CV ($q_{u,jg,str}$): coefficient of variation of the uniaxial compressive strength, related to the entire plug structure.
- $q_{u,jg,k}$: characteristic uniaxial compressive strength of the treated soil, related to the imposed percentile of the distribution of $q_{u,str}$.
- $h_{jg,uplift}$: minimum height of the jet grouted part of the plug needed for uplift equilibrium.
- $h_{jg,bending}$: minimum height of the jet grouted part of the plug needed for rotational equilibrium.
- $h_{jg,min}$: minimum plug thickness (equal to the maximum between $h_{jg,uplift}$ and $h_{jg,bending}$).

The software also plots the Log-Normal distributions of both $q_{u,jg,spec}$ and $q_{u,jg,plug}$, showing the effect of the parameter λ

The partial factors can be selected according to the reference standards (EuroCode or Italian Building Code NTC2018 are available in the code), as shown in Table 1, or just set to 1 to avoid considering codes' indications and solving the non-factorized equilibrium equations.

Possible ranges of values of CV($q_{u,jg,spec}$) and CV(D) are reported in Table 2 and Table 3, and can be used as a reference.

Table 1. Values of the partial factors γ_V γ_G and γ_{qu} for the uplift and bending mechanisms.

DropDown Menù	γ_V	γ_G	γ_{qu}	Failure Mechanism
EuroCode	1	0.9	1.4	***UpLift***
	1.35	0.9	1.4	***Cracking***
NTC 2018	1.1	0.9	1.4	***UpLift***
	1.1	0.9	1.4	***Cracking***

Table 2. Ranges of values of the coefficient of variation of the uniaxial compressive strength of the jet grouted material at the scale of laboratory specimens, based on some experimental evidences. The value of CV(qu,spec) largely depends on the adopted technology and on the treatment procedure. Therefore, the values reported in the table are just reference values published in literature.

	Soil grading		
	Silty-clayey	*Sandy*	*Sandy-gravelly*
CV($q_{u,jg,spec}$)	0.40-0.75	0.15-0.30	0.25-0.50

5. Grid Generation Section

Once the minimum plug thickness has been assessed, the software can calculate the expected voids (untreated volume) within the jet grouted part. This calculation is carried out assigning the columns layout at ground level (Figure 6). The following input data are required:

- $s_{x,y,}$, s_T: spacing between the columns. Different layout options are possible: square grid (**A**), square grid with a central column (**B**), quincunx grid (**C**). The spacings must be assigned accordingly, once the option A, B or C has been chosen from the drop-down menu.
- n° L and n° B: additional edge columns (optional). Since along the edges additional care may be required to avoid untreated parts of the plug, this option allows to introduce extra columns along them.
- DL and DB: if edge columns are added, these are the distances of the centres of the additional columns respectively from the longer (L) and the shorter (B) edges.
- D_m: average diameter of the jet grouted columns.

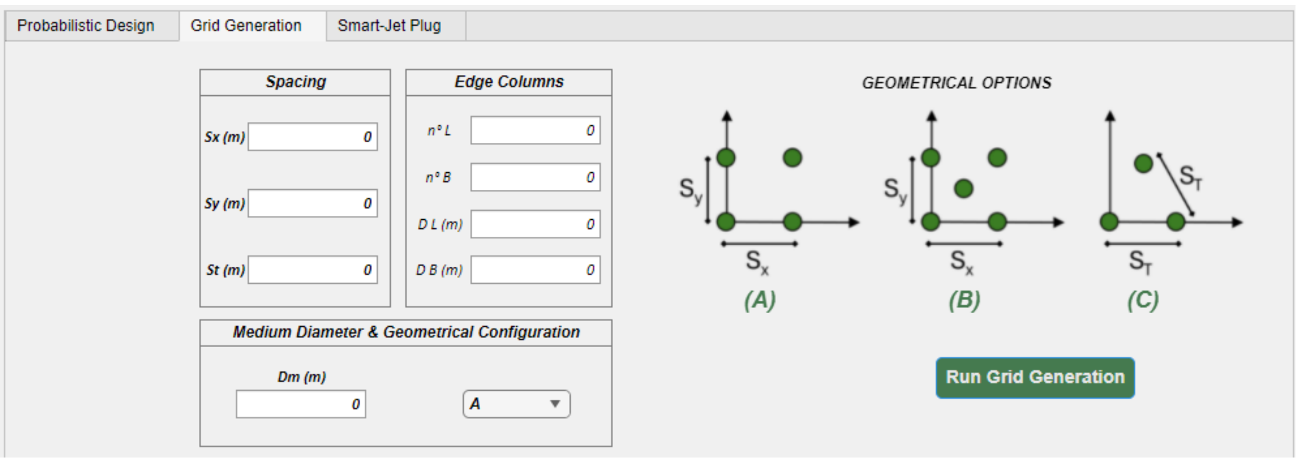


Figure 6. Grid Generation screen.

The ***Run Grid Generation*** command allows to draw the geometrical layout at ground level of the columns (Figure 7). Such a layout is the ideal one, i.e. corresponds to the layout at any depth only if no random variability of the columns' axis position and columns' diameter is considered.

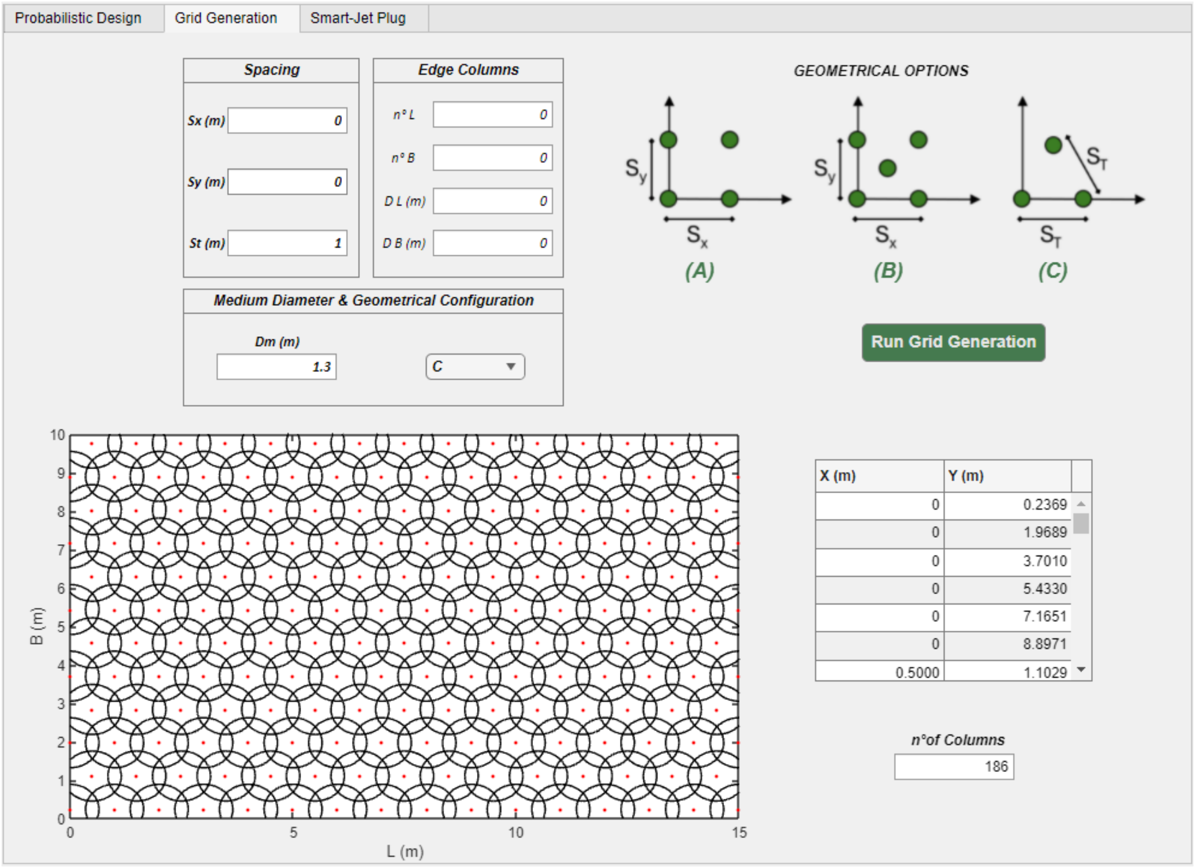


Figure 7. Spatial distribution of the columns centres and average diameter.

6. Water flow calculation

Once the layout has been properly set, the code allows to consider the random variability of columns position and diameter (from column to column, and for a given column at any depth) to calculate the untreated volume of the jet grouted part of the plug, and thus the water flow through it. To this aim, a probabilistic calculation is carried out with the Monte Carlo procedure to estimate the defects of the jet grouted part of the plug, i.e. the parts that are not treated because of the random variability of the columns' axis and diameter.
The diameter of the columns is considered to have a Gaussian distribution of probability, while the position of the jet grouted column is given by the two angles α (inclination) and β (azimuth) (Figure 8). The inclination α is considered to be normally distributed with a mean value equal to zero (thus needing only to quantify the scatter), while the azimuth β is considered to have a uniform distribution of probability, thus needing no input parameters.
The calculation screen of this section is reported in Figure 9. The software allows to calculate the untreated area in each section of the jet-grouted part of the plug assuming a given value of the probability PF% of being non conservative (i.e. of having larger untreated areas). The confidence interval CI set in the software calculation routine is 95%. Such a confidence is achieved with a possible error e% (given in percentage). There is a theoretical correlation between pf%, CI and e% that univocally sets the number of iterations needed in the calculation (Figure 10). As shown in the figure, the correlation is strongly non-linear, and therefore if a low value of pf% is desired with a low error e%, the number of iterations can increase enormously. The computational time of this step depends on the required values of pf% and e%.

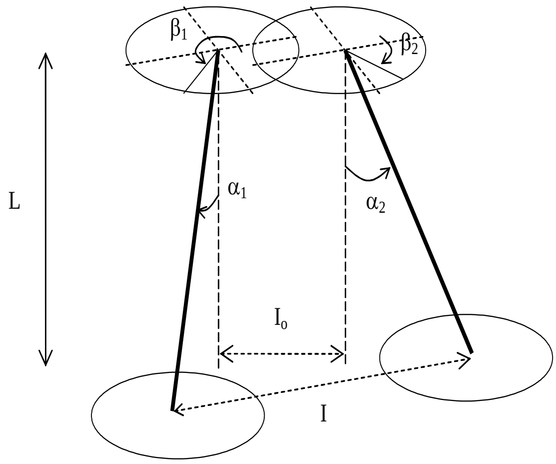


Figure 8. Definition of the azimuth (α) and inclination (β), whose values define the position of the column axis.

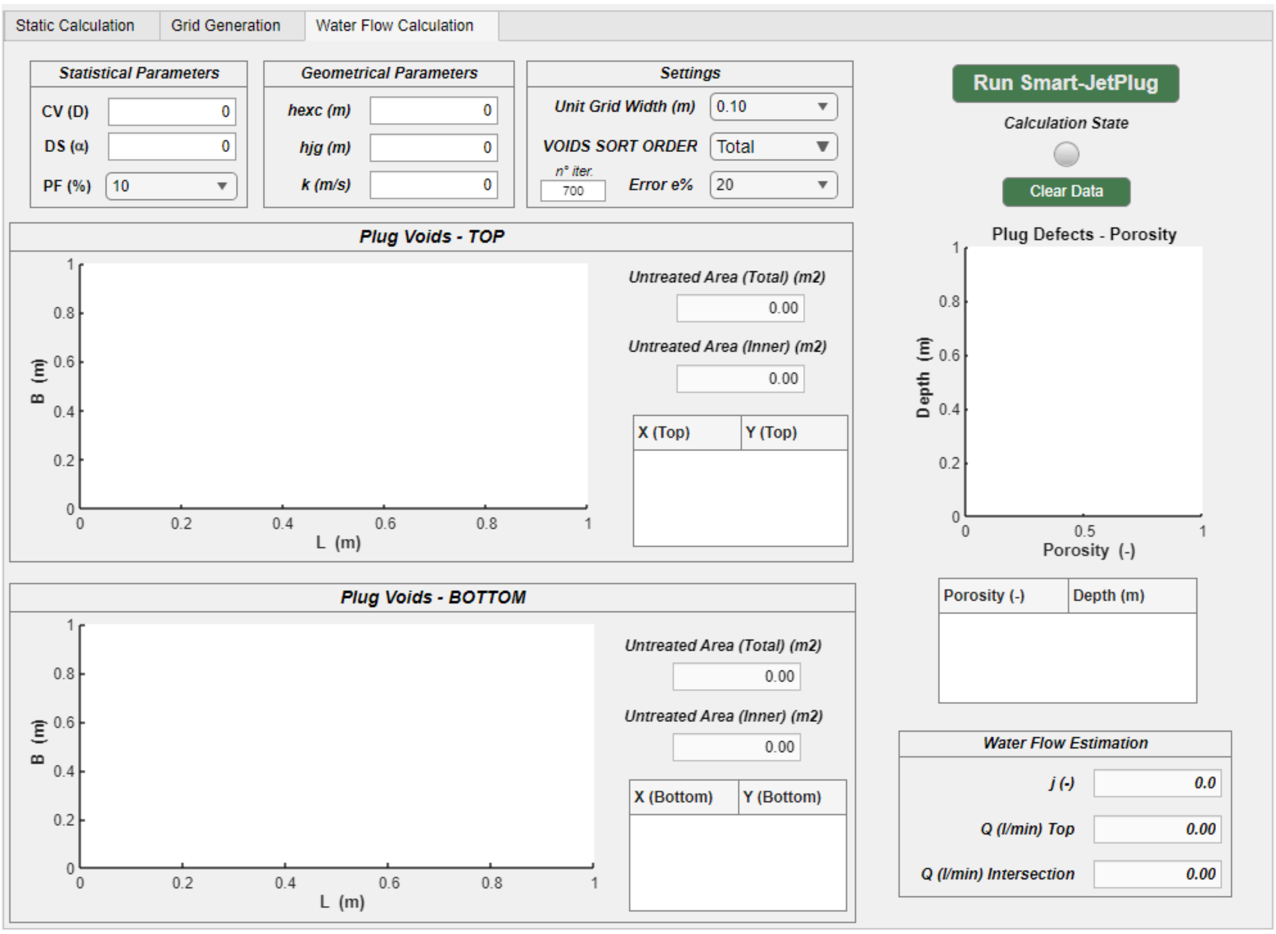


Figure 9. Input parameters for JetPlug code-voids statistical estimation.

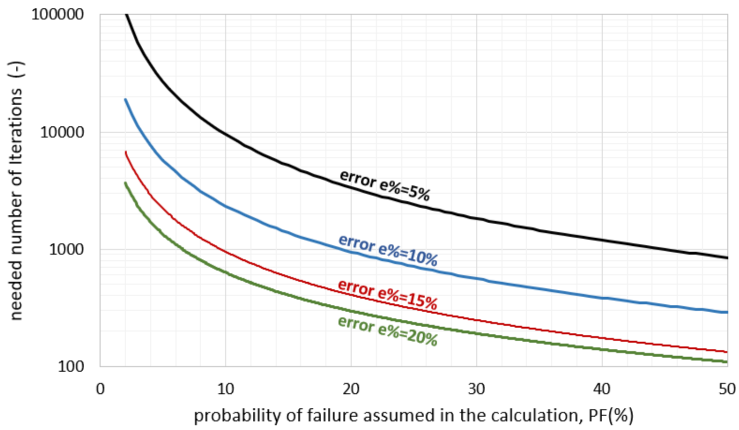


Figure 10. Number of iterations done by the calculation routine of Smart JetPlug as a function of the assumed values of PF% and e%.

The code asks for:

- CV(D): coefficient of variation of the columns' diameter.
- DS (α): standard deviation of the columns' inclination (°).
- PF (%): the probability of failure for the Monte Carlo calculation, intended as the probability that along the jet grouted height the plug has untreated parts having and area larger than the one estimated with the calculation. The values 2%, 5%, 10%, 20%, 30% or 50% can be assigned.
- e%: the accepted error. The values 5%, 10%, 15%, 20% can be assigned.
- h_{exc}: excavation height (m).
- h_{jg}: plug thickness (h_{jg} must be set as an integer) (m).
- k: soil permeability at the depth of the jet grouted part of the plug (m/s).

Typical ranges of values of CV(D) are given in Table 3 as a function of soil heterogeneity.

Table 3 Typical ranges of values of the coefficient of variation of the jet grouted columns' diameter (Croce et al. 2014).

	Soil heterogeneity		
	Low	*Medium*	*High*
CV(D)	0.02-0.05	0.05-0.10	0.05-0.20

The software allows to set the unit grid width for the generation of the control mesh. Two values of the untreated area are given: the total value and the inner value, the latter intended as that calculated neglecting the untreated parts at a distance smaller than $D_m/2$ from the edges. The water flow calculation can be then carried out considering the two possible options, to be assigned in the VOID SORT ORDER drop-down menu (i.e. total or inner water flow).
Once the input data have been assigned, clicking on the ***Run Smart-JetPlug*** button the probabilistic calculation is carried out. The calculation time strongly depends on the choice of PF% and e%. Values of PF%<5 are not recommended because they may correspond to a huge number of iterations, depending on the requested value of e%.
Once the calculation is complete, the plots with the spatial distribution of the untreated areas at the top and the bottom of the jet grouted part of the plug are displayed (as shown in Figure 11).
In the "*Water Flow Estimation*" panel, the overall water flow values are reported, considering two possible values: the one corresponding to the untreated area at the top of the jet grouted part of the

plug and the one corresponding to the untreated areas that are vertically aligned in such a way to generate a channel ($Q_{intersection}<Q_{top}$).

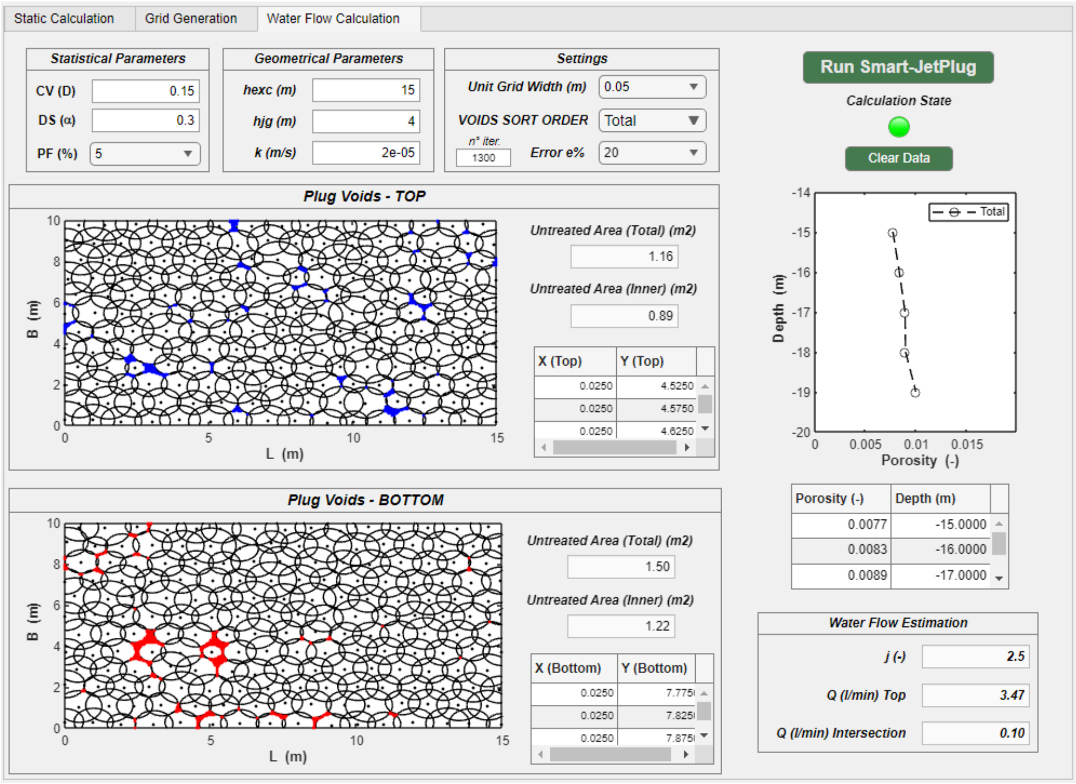
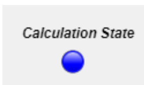
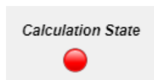
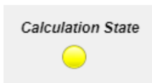
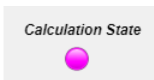
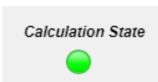


Figure 11. Example of water flow calculation output results.

This latter value may differ from run to run, considering the probabilistic nature of the calculation. The state of calculation is displayed as indicated in Table 4.

Table 4. Calculation Indicators.

	*Initialization*
	*Calculation of the n scenarios*
	*Iterations ordering*
	*Calculation of the needed iteration*
	*End of calculating*

When the software is launched, it may take a few minutes for the command window to become visible.

7. References

Croce, P., Flora, A., Modoni, G. (2014). **Jet Grouting: Technology, Design and Control**. CRC Press, 279 pp.

Erto,P. (2008). **Probabilità e statistica per le scienze e l'ingegneria**. 3° Edizione, McGraw-Hill.

Flora, A., Modoni, G., Lirer, S., Croce, P. (2013). **The diameter of single, double and triple fluid jet grouting columns: Prediction method and field trial results**. Geotechnique, 63(11), pp. 934-945.

Modoni, G., Flora, A., Lirer, S., Ochmański, M., Croce, P. (2016). **Design of jet grouted excavation bottom plugs**. Journal of Geotechnical and Geoenvironmental Engineering, 142(7),04016018.

Toraldo C., Modoni G., Ochmanski M., Croce P. (2018). **The characteristic strength of jet-grouted material**. Geotechnique, 68(3), 262 – 279.

8. Warning and disclaimer

Smart-JetPlug is a software conceived for designing jet grouted bottom plugs (i.e. bottom plugs obtained by partial overlapping of jet grouted columns) with reference to static and hydraulic limit states, using a probabilistic approach to consider the random variability of grouted columns position (axis deviation), diameter and strength. Every effort has been made to ensure the accuracy of Smart-JetPlug. Users must acknowledge their own responsibility when utilizing the computational results for geotechnical design purposes. Smart-G s.r.l. cannot be held responsible or liable for any design errors resulting from the use of Smart-JetPlug calculations.

EXAMPLE

In this section a detailed example of Smart-JetPlug calculation is reported.

- **Static Calculation**

The tested plug is a 20 m x 10 m, with a Δh_w equal to 12 m. The unit weight of the jet grouted soil is set to 18 kN/m^3. In this case, since h_s is set to zero (i.e. no untreated soil is considered above the jet grouted plug), the value γs can be even unset.

The shear strength angle is equal to 30° and an average uniaxial compressive strength of the treated soil at the specimens' scale, $q_{u,jg,spec}$, is equal to 2 MPa. If a semi-probabilistic analysis wants to be performed, it is mandatory to set the values CV($q_{u,jg,spec}$) and λ in order to allow the code for calculating CV($q_{u,jg,plug}$)=λ·CV($q_{u,jg,specimens}$) (Figure 12). The percentile of the uniaxial compressive strength is automatically set to 5%, but it can be changed by the user.

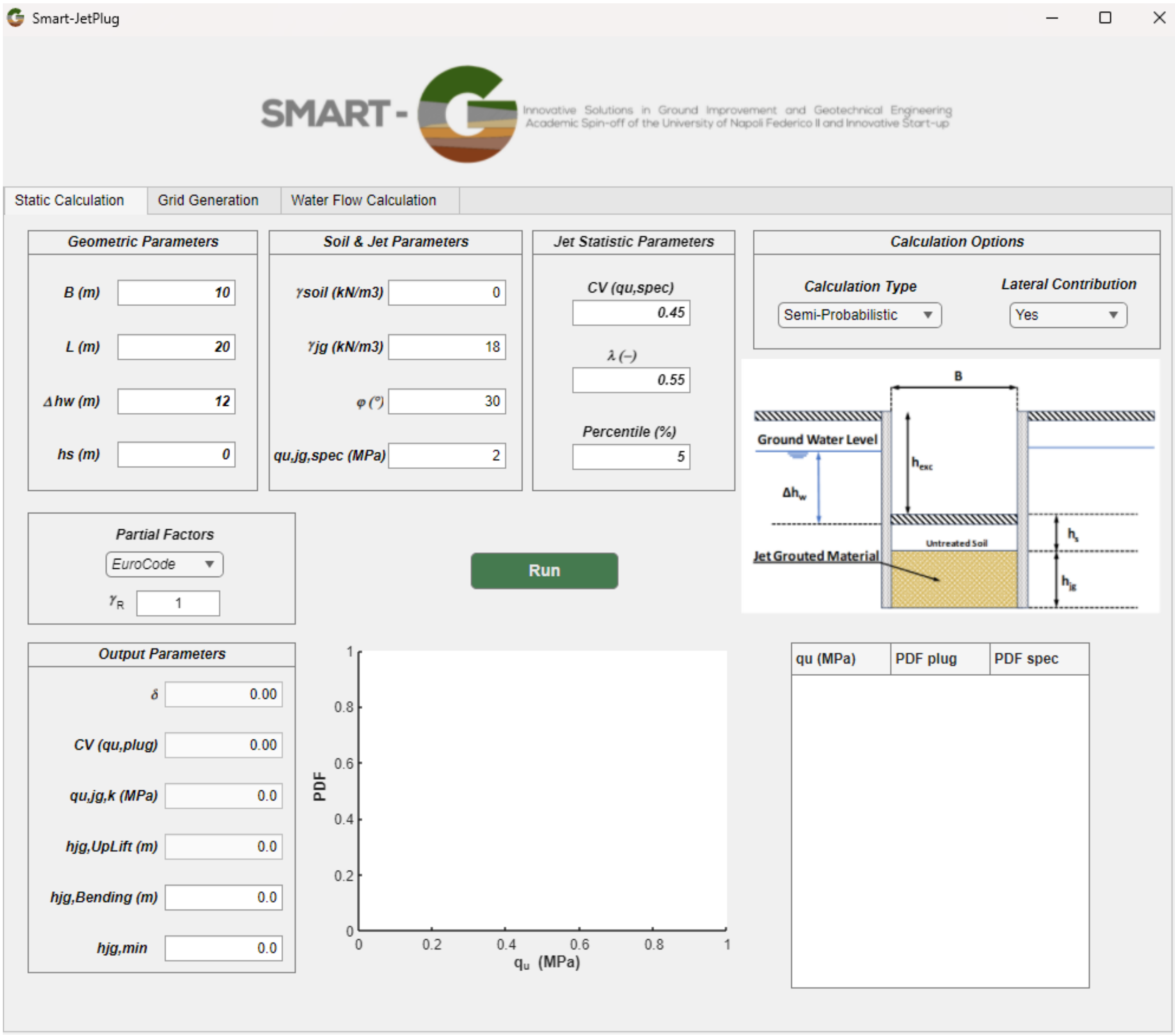


Figure 12. Input data set for a semi-probabilistic calculation of the plug's thickness.

If such an input is run, the program returns the *Output Parameters* reported in Figure 13, showing the CV($q_{u,jg,plug}$) used for the determination of the uniaxial compressive characteristic strength, $q_{u,jg,k}$, and the plug's thicknesses for both the considered failure mechanisms (uplift and bending). The final value $h_{jg,min}$ is the maximum between $h_{jg,UpLift}$ and $h_{jg,Bending}$. In addition, both the log-normal statistic distributions are plotted, in order to give an idea of the practical consequences of considering the strength variability related to the entire plug. Indeed, if such an issue is taken into account, the design value of $q_{u,jg,k}$ is higher.

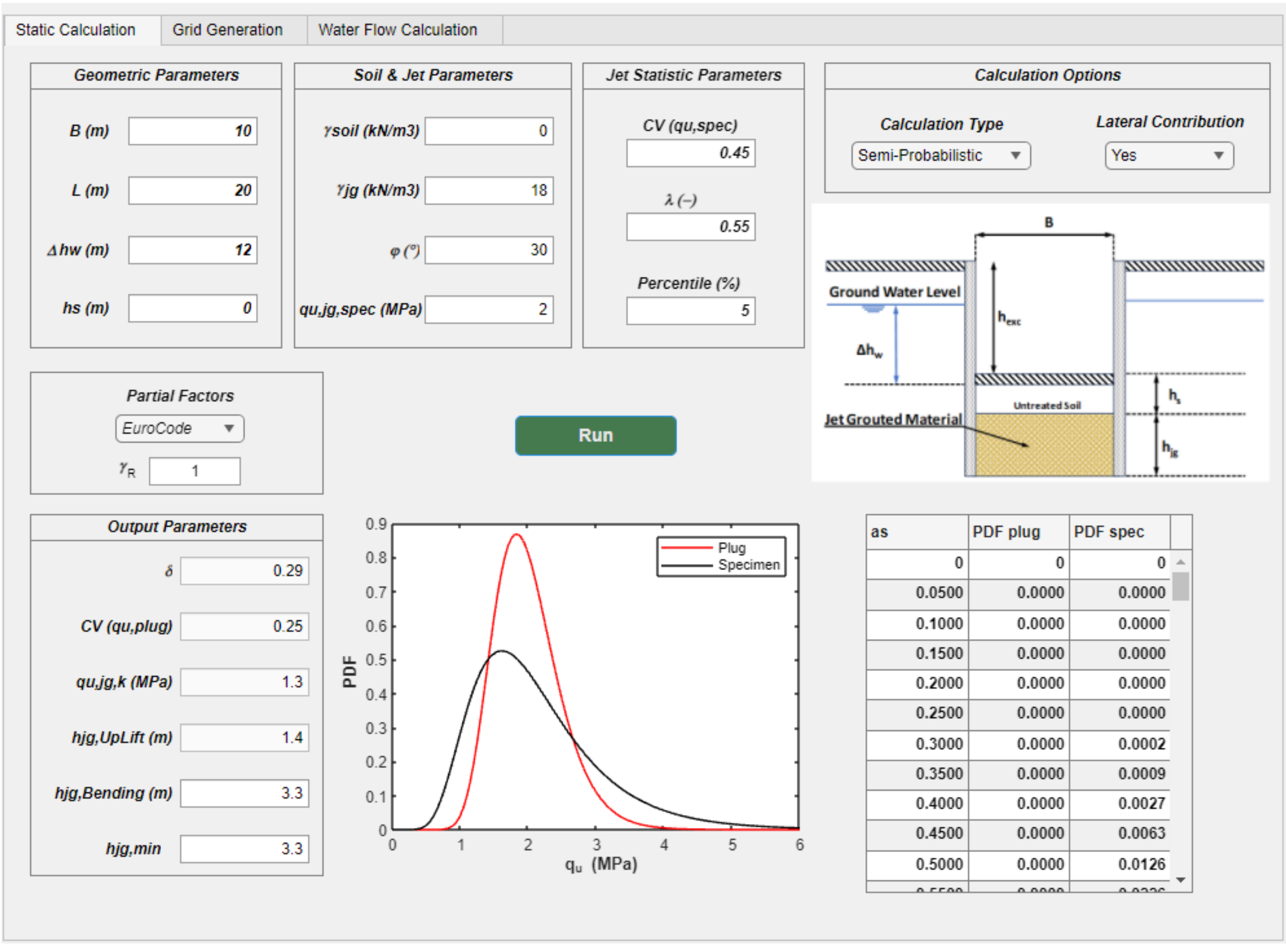


Figure 13. Output parameters for a semi-probabilistic calculation of the plug's thickness.

Anyway, the program allows even to not consider the statistical aspects of the uniaxial compressive strength. Thus, if "Deterministic" calculation option is selected, the program does not consider any kind of statistical law and strength variability:

$$q_{u,jg,spec} = q_{u,jg,plug} = q_{u,jg,k}$$

In this case no statistical distribution will be plotted in the output window (Figure 14). The software does not consider the eventual values set in the "*Jet Statistic Parameters*".
Finally, the program also allows to not consider the positive contribution of the lateral shear strength in the calculation of $h_{jg,uplift}$. Such an analysis will show only the results related to the UpLift failure mechanism, since the lack of the lateral shear strength makes the bending failure mechanism impossible. The outcome of the analysis with no lateral contribution for the current example is reported in Figure 15.

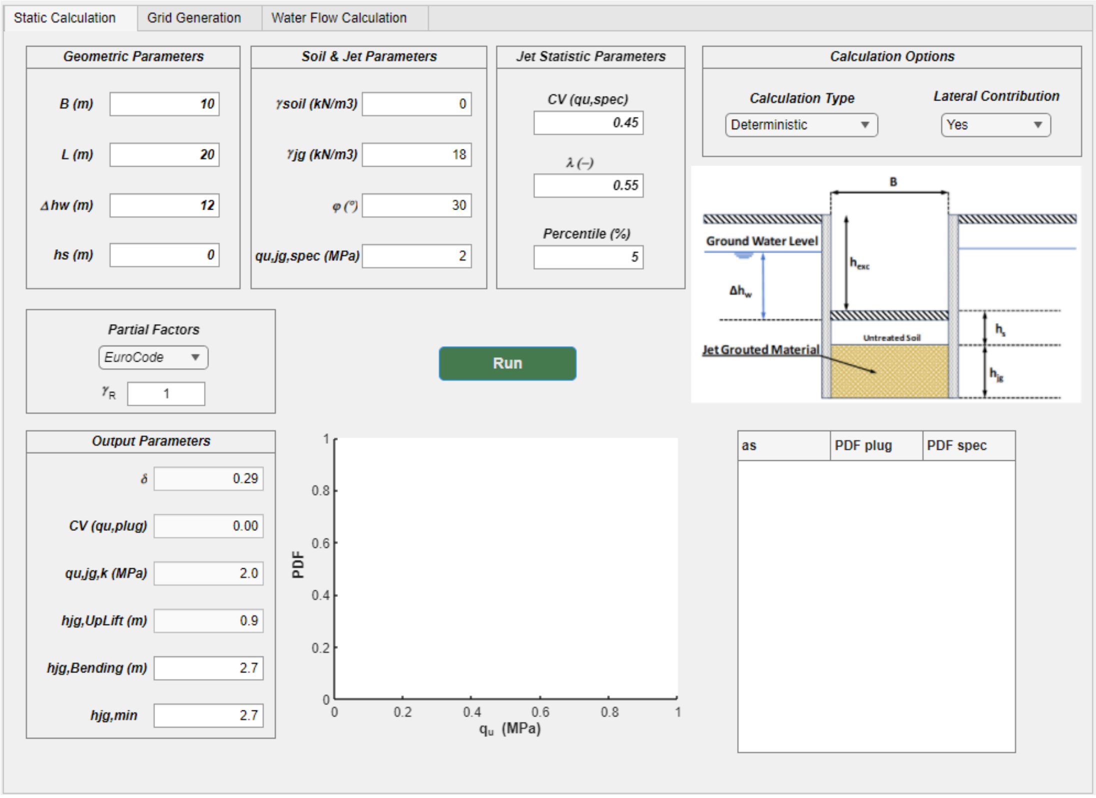


Figure 14. Output parameters for a deterministic calculation of the plug's thickness.

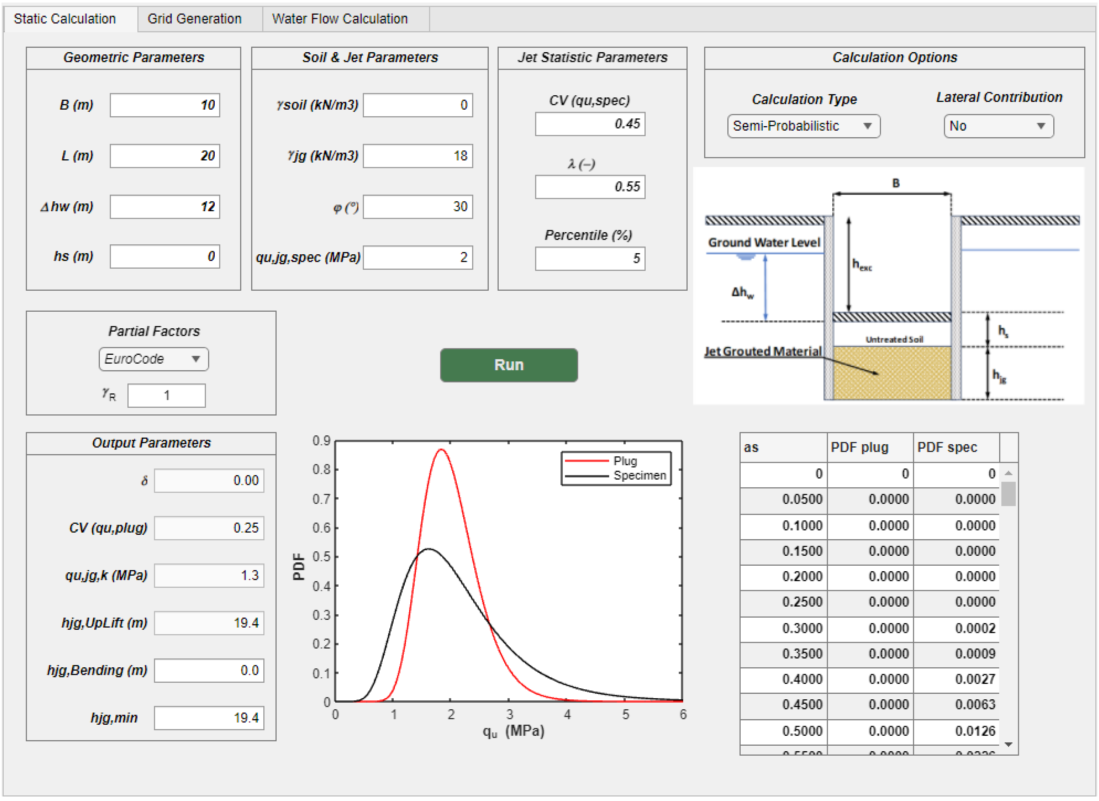


Figure 15. Output parameters for a semi-probabilistic calculation of the plug's thickness with no lateral contribution.

Thus, the same geometrical configuration of the plug (20 m x 10 m) can give different values of $h_{jg,min}$, as a function of the user's consideration on the specific plug's design.
The following of the current example is referred to:

- Calculation type: *Semi-Probabilistic*
- Later Contribution: *Yes*

for a minimum plug thickness $h_{jg,min}$ equal to 3.3m.

- **Grid Generation**

For the determination of the columns' layout at ground level a triangular distribution is set, adopting a spacing s_T=0.90 m and an average diameter D_m=1.20 m (input in Figure 16, output in Figure 17).

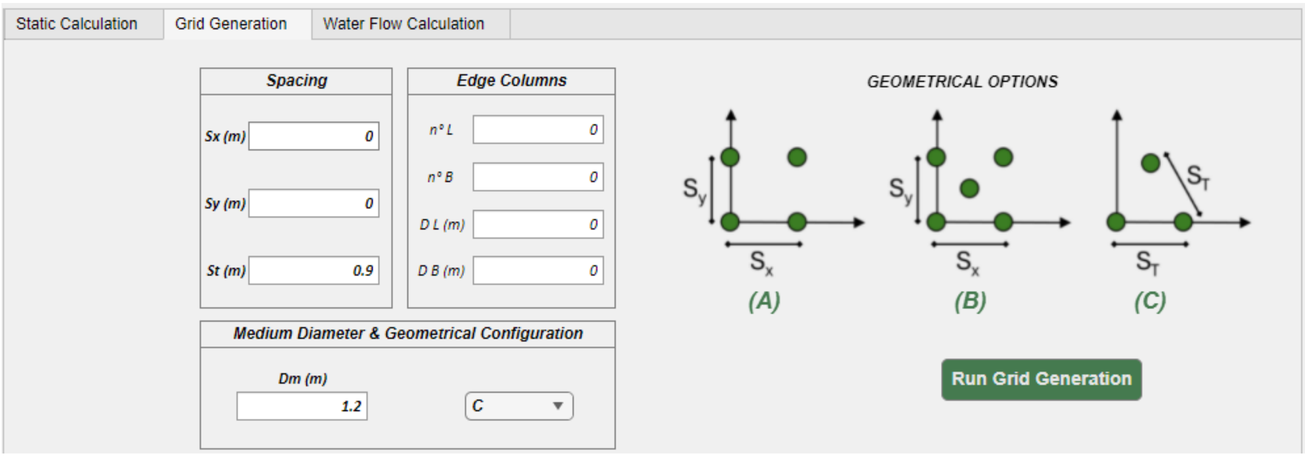


Figure 16. Grid generation input for a triangular geometric option.

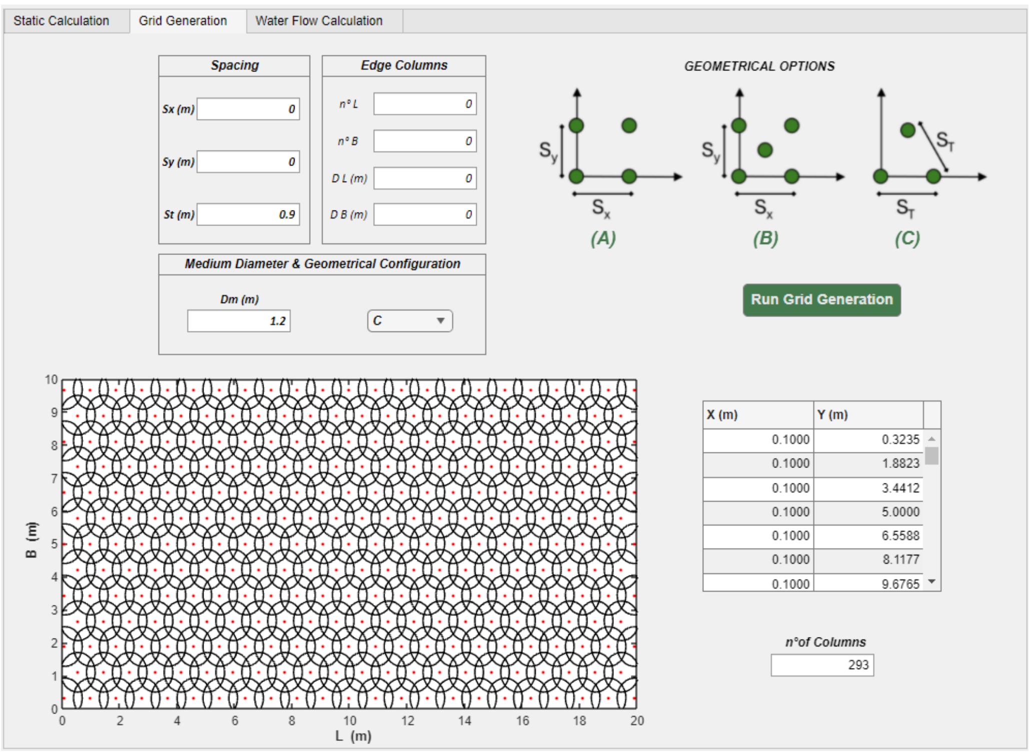


Figure 17. Grid generation output for a triangular geometric option.

In the output the software will plot the ideal configuration of the treatment at ground level, the total number of columns and the centre's coordinates of the columns themselves.

- **Water Flow Calculation**

At this stage, the water flow estimation due to the eventual untreated area can be performed. To do so, the input parameters of CV(D), DS(α), PF(%), e(%) and all the remaining geometric parameters have to be set. In the current example, all the input data are reported in Figure 18.

<u>Note that in the "Static Calculation" a minimum plug's thickness of 3.3 m is needed. Since the software allows to set plug's thickness only as an integer, in the calculation a h_{jg}=4.0 m has been adopted.</u>

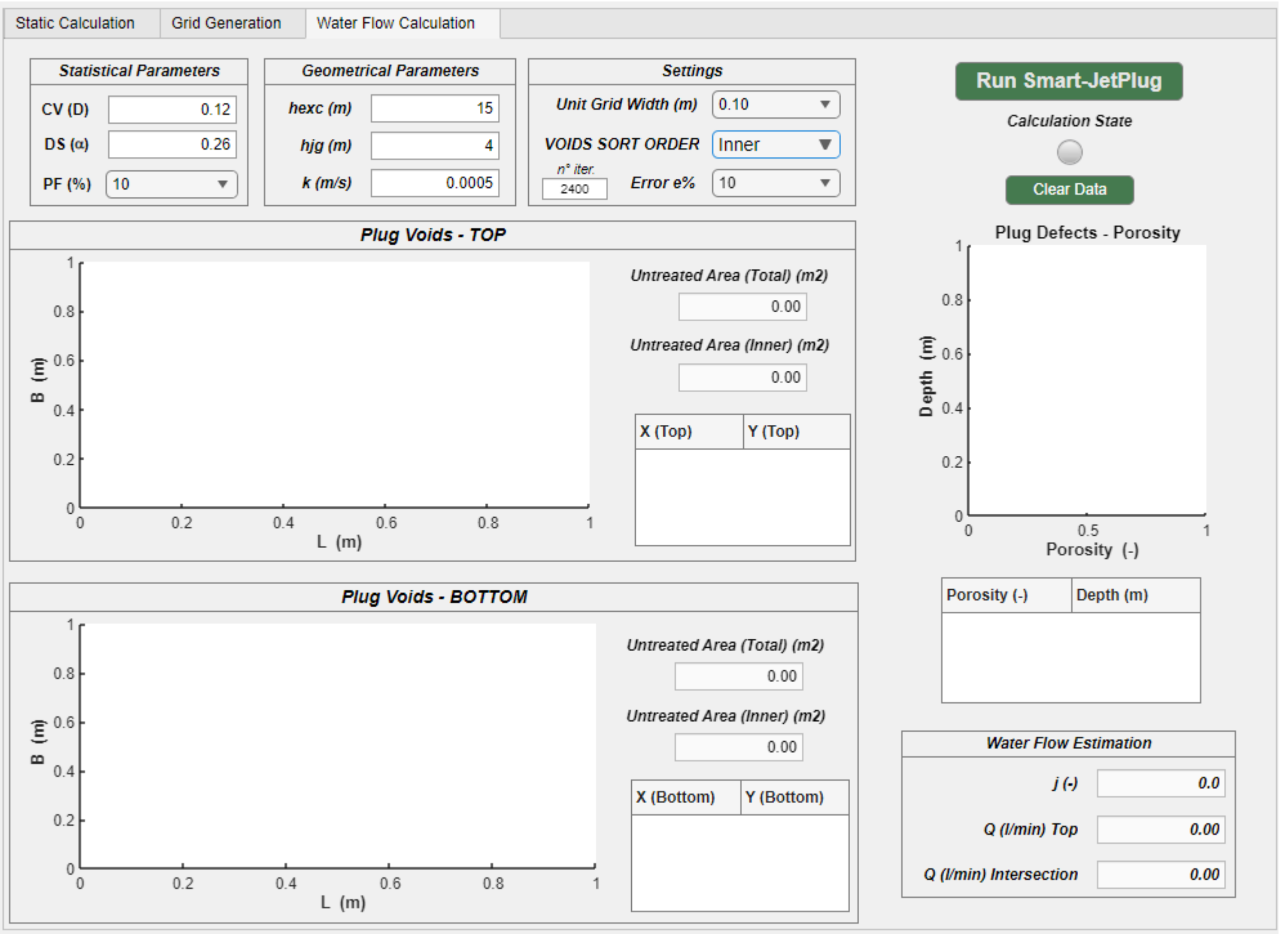


Figure 18. Input setting for the water flow estimation.

Finally, as the "***Run Smart-JetPlug***" button is activated, the software will perform all the calculations for the "*n° iter*" scenarios (equal to 2400 for a PF=10% and e=10%). The calculation time is strongly dependent on the number of iterations.

The typical screen output is reported in Figure 19, in which all the parameters of interests depicted in the manual are clearly reported.

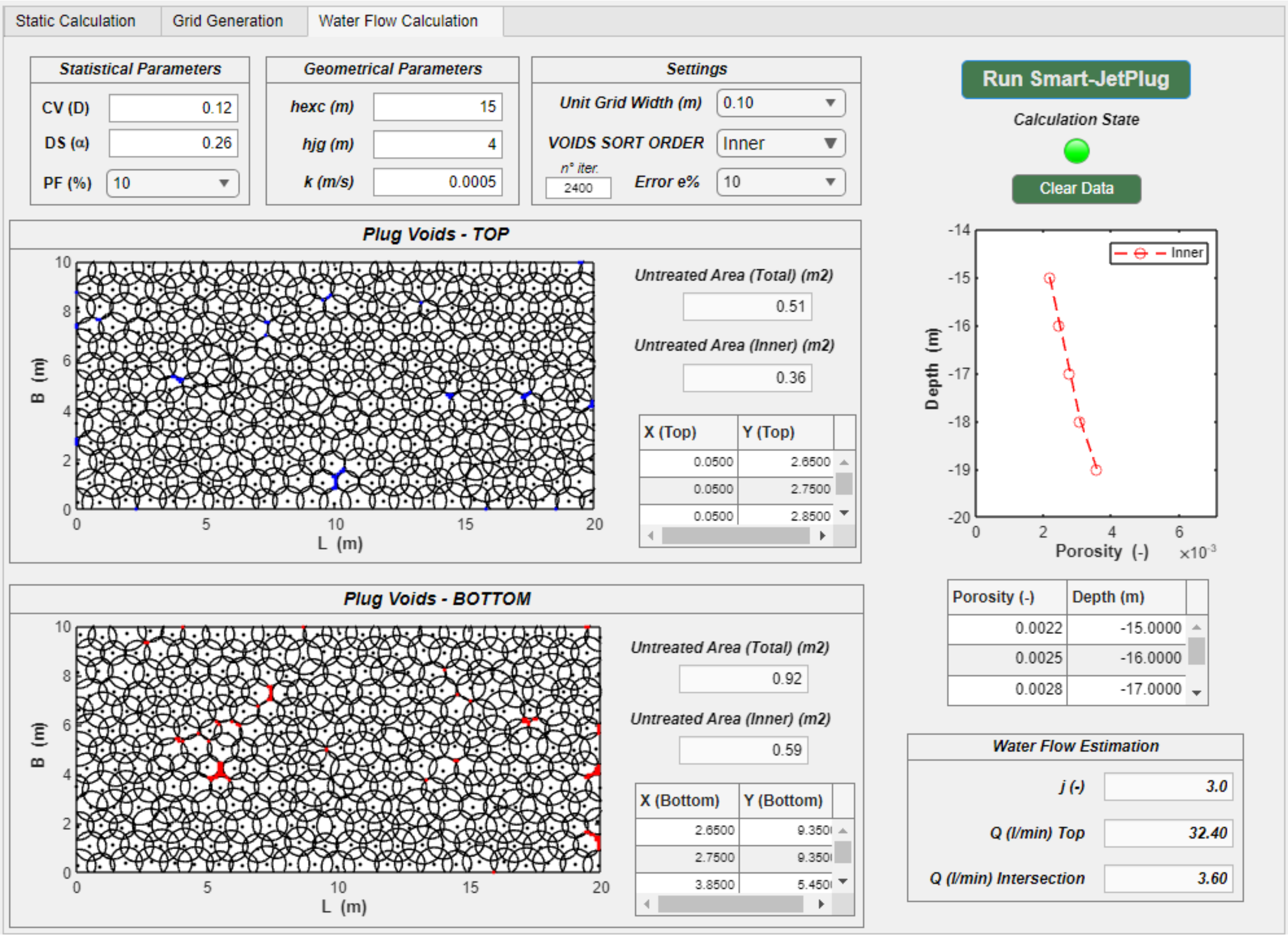


Figure 19. Output result screen for the water flow estimation.

In addition, all the plots contained in each panel can be easily saved by the user. Some examples are reported in the following.

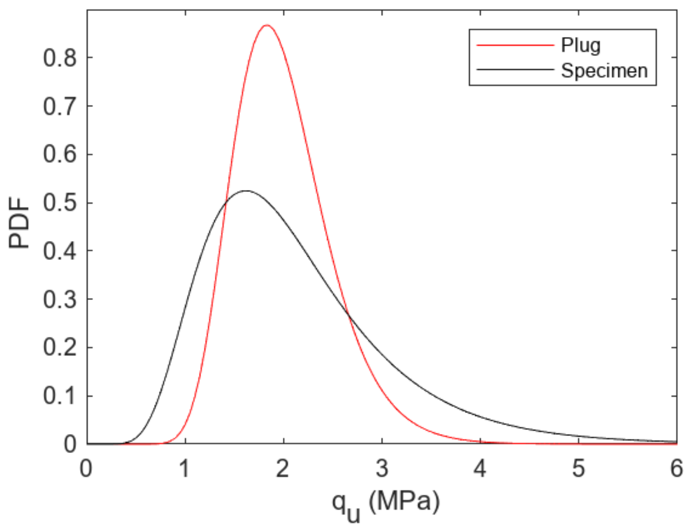


Figure 20. Log-normal distributions.

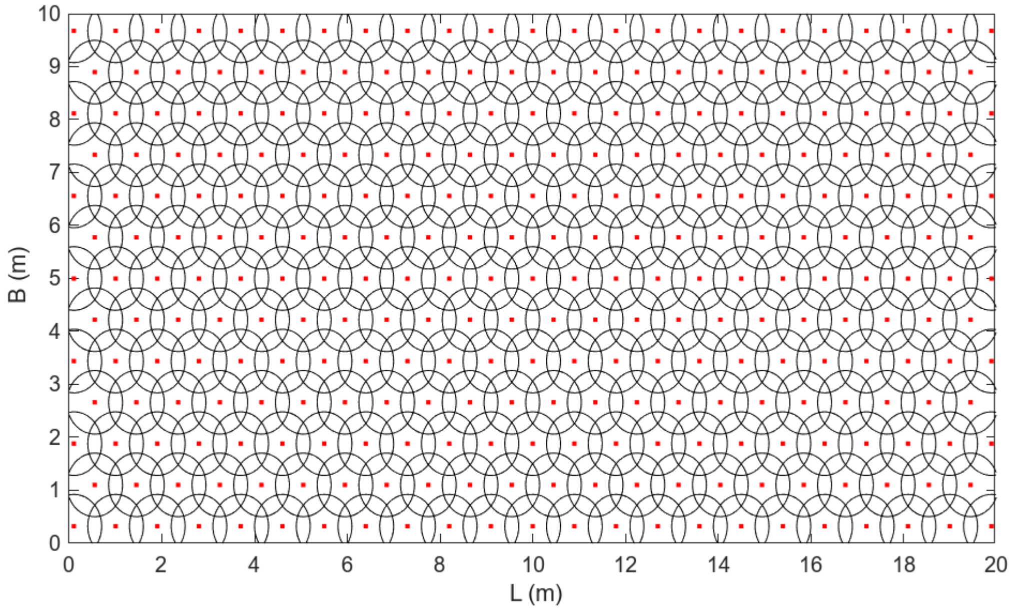


Figure 21. Ideal geometrical configuration at ground level.

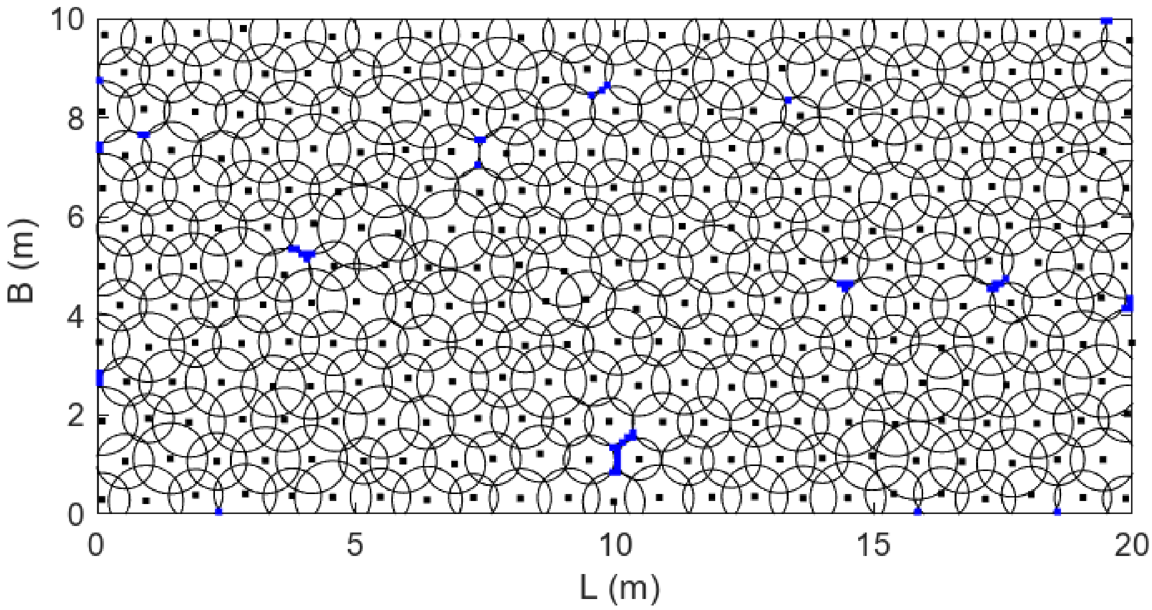


Figure 22. Untreated area estimated at the top of the plug.

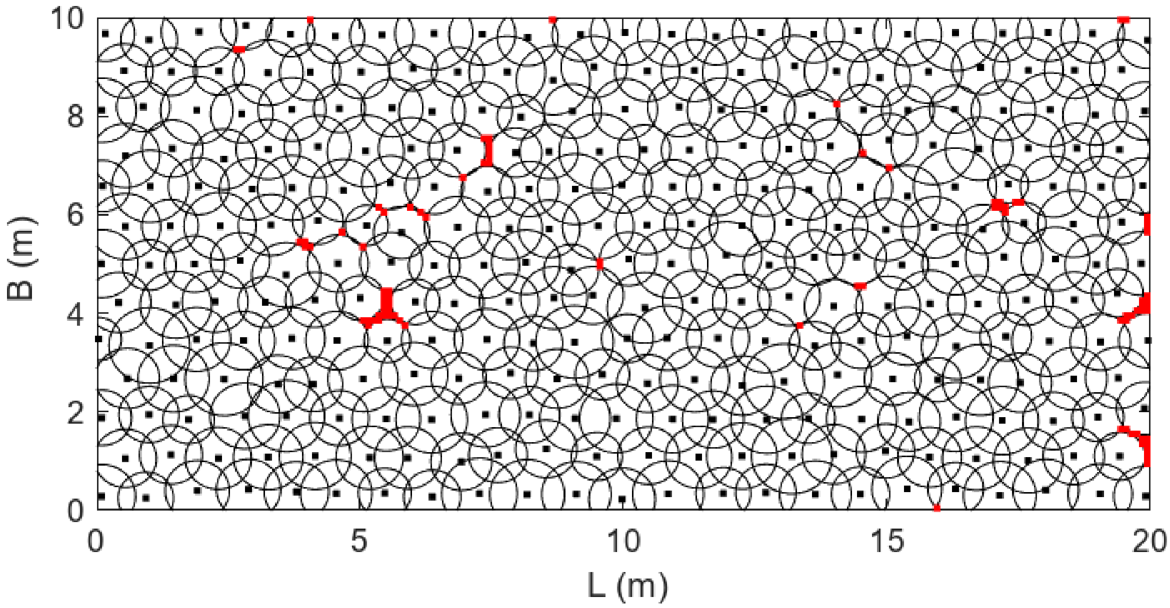


Figure 23. Untreated area estimated at the bottom of the plug.

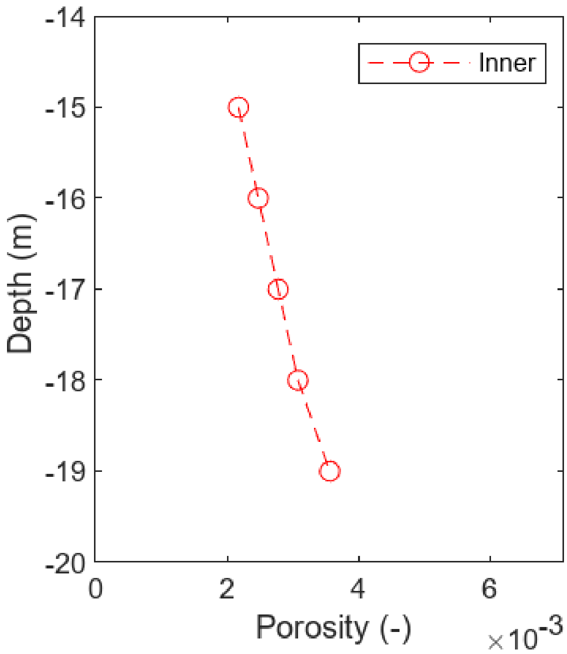


Figure 24. Porosity of the plug vs. depth due to untreated areas.