

Application Note - Cantilever Stem Wall Analysis

1 Introduction

This note describes the typical steps followed in setting up and analysing a cantilever stem wall stability problem with LimitState:GEO. It also highlights some of the differences in approach to those adopted by commonly used limit equilibrium analysis methods.

All files used in this note are available in a zip file that can be downloaded from http://www.limitstate.com/files/application-notes/LSGAN4/cantilever_wall_analysis.zip

Familiarity with the use of LimitState:GEO is assumed. The reader is referred to the user manual for further information on any features discussed in this note.

2 Problem definition

The specified problem depicted in Figure 1 involves analysis of a 5 m high reinforced concrete cantilever T wall backfilled with granular material. The backfill, adjacent stratum of stiff clay and the wall are underlain by loose sand. The surfaces of the backfill and stiff clay are level with the top of the wall and support a variable surcharge of 10 kN/m². The problem is to be checked against Eurocode 7 Design Approach 1 requirements for long term conditions. The water table lies well below the wall foundation and for simplicity it is assumed that water pressures in the clay are effectively zero. Passive resistance of the soil in front of the wall is to be included.

Both external failure (e.g. sliding, bearing) and internal failure (wall bending, shearing) are to be investigated. Note that a traditional approach to investigating internal bending and shear failure is to determine the pressure distribution along the wall and then calculate bending moments manually. With LimitState:GEO it is recommended to use the software to identify bending/shear failure directly. This also ensures the correct overall failure mechanism is modelled for that type of failure mode.

The main problem geometry is available as a dxf file ([cantilever_wall.dxf](#)). The modelled soils and associated parameters are listed in Tables 1 and 2 in Section 3. The internal wall properties are listed in Tables 3 and 4.

Details of how to set up the problem manually are given in Section 3. To skip direct to the analysis stage, please go to Section 4.

3 Setting up problem geometry, materials and loading

Creation of the LimitState:GEO model was undertaken in the following stages:

- 1) Import the geometry from [cantilever_wall.dxf](#) using the **File/Import from Dxf...** function. Remove any residual construction lines using **Draw/Construction Line/Clear All** since these will not be needed. Alternatively the model can be created using the built in stem wall wizard.
- 2) Define soil and wall material properties as listed in Table 1. Create Granular Backfill and Wall materials using **Tools/Create New Material...** and apply together with default materials *Stiff Clay* and *Loose Sand* to the appropriate **Solids** by drag and drop. Note that ϕ' in Table 1 and elsewhere in this Application Note is conservatively set as the critical state angle of shearing resistance i.e. $\phi' = \phi'_{\text{crit}}$.

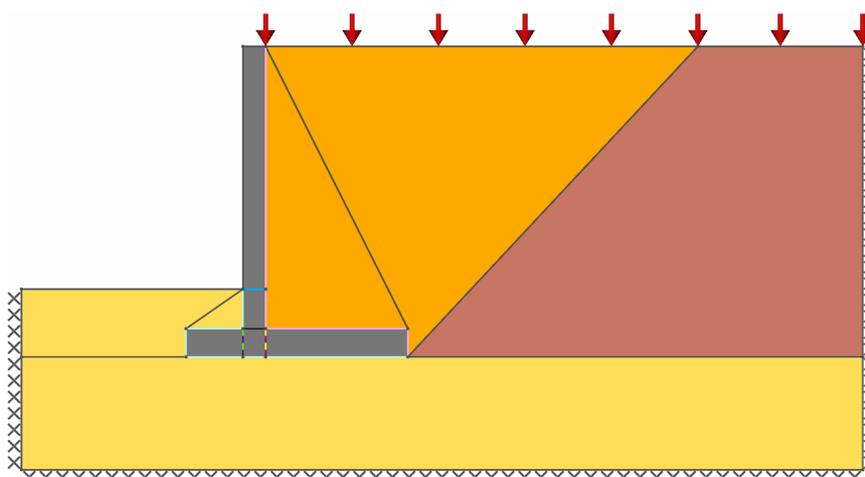


Figure 1: Cantilever wall problem geometry

Soil	Material type	Material drainage behaviour	c_u (kN/m ²)	c' (kN/m ²)	ϕ'	γ (kN/m ³)	γ_{sat} (kN/m ³)
Granular Backfill	Mohr-Coulomb	Always drained	-	0	32°	19.5	21
Loose Sand (default)	Mohr-Coulomb	Always drained	-	0	30°	14	19
Stiff Clay (default)	Mohr-Coulomb	Drained/undrained	120	4	22°	21	21
Wall	Rigid	-	-	-	-	24	24

Table 1: Soil properties

Alternatively for this example these and additional (to be used later) pre-defined materials may be imported from [cantilever_wall.csv](#) using the **Tools/ Import Materials...** function. Materials are named by the type of **Solid** or wall **Boundary** to which they should be applied.

- Define soil/structure interface properties as listed in Table 2 using **Tools/Create New Material...** Apply created materials to the appropriate **Boundaries** by drag and drop. It is assumed that the soil/wall friction angle $\delta = (2/3)\phi'_{crit}$. For more information on soil/structure interface properties in LimitState:GEO see the Application Note: **Gravity Wall Analysis LS-G-AN3**.

Soil/wall interface	Material type	Material drainage behaviour	c_u (kN/m ²)	c' (kN/m ²)	ϕ'	γ (kN/m ³)	γ_{sat} (kN/m ³)
Loose sand - Wall	Mohr-Coulomb	Always drained	-	0	20.0°	0	0
Backfill - Wall	Mohr-Coulomb	Always drained	-	0	21.4°	0	0

Table 2: Soil/wall interface properties

Key modelling concept: *modelling structural elements in LimitState:GEO*

The recommended method for including the possibility of structural failure in a LimitState:GEO analysis involves the addition of specific **Boundaries** in the structure anywhere where it is expected to fail in bending and/or shear. The remainder of the structure is modelled as a **Rigid** material.

A **Boundary** modelled with a **Cutoff** material i.e. with a **Limiting tensile stress** (σ_T) and **Limiting compressive stress** (σ_C) can be used to allow rotational failure at that point in the structure. Such a boundary models a plastic hinge at the ultimate limit state using rectangular stress blocks (as typically used in plastic beam analysis). The full plastic moment can be calculated using the following equation:

$$M_p = \sigma_y \frac{bd^2}{4} \tag{1}$$

where $b = 1.0$ (since the problem is two-dimensional) and $\sigma_y = \sigma_C = \sigma_T$.

A shearing surface is modelled with a **Mohr-Coulomb** material. The cohesion (c_u) represents the shear strength of the structural element. If the shear strength V_{RD} of the element is known in kN the cohesion specified in LimitState:GEO is calculated as: $c_u = \frac{V_{RD}}{d}$; where d is section depth.

For more information see Technical Note: **Modelling Structural Resistance LS-G-TN4**.

- 4) Define the strength of the wall as listed in Tables 3 and 4 using **Tools/Create New Material...** Apply created materials to the appropriate internal wall **Boundaries** by drag and drop. Note that in this example these internal boundaries are defined only at the junction of the stem (1), toe (2) and heel (3) and in the stem at the soil surface level (4) on the passive side of the wall (see Figure 2). These correspond to the locations where bending and/or shear failure might be expected to occur in the wall. It will be necessary to create a combined material on these boundaries to accommodate modelling of both shear and bending.

Structural part	Material type	Limiting tensile/compressive stress (kN/m ²)	Equivalent bending resistance (kN.m)	Section depth (m)
Stem Bending	Cutoff	5000	200	0.4
Toe Bending	Cutoff	3000	187.5	0.5
Heel Bending	Cutoff	3000	187.5	0.5

Table 3: Design wall bending resistance

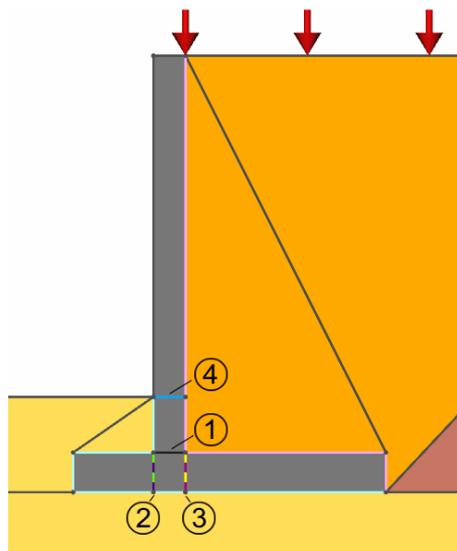


Figure 2: Cantilever wall - details of internal boundaries where yield is to be checked

Structural part	Material type	Material drainage behaviour	c_u (kN/m ²)	Thickness t (m)	Equivalent shear resistance $c_u t$ (kN)
Stem Shear	Mohr-Coulomb	Always undrained	600	0.4	240
Toe Shear	Mohr-Coulomb	Always undrained	200	0.5	100
Heel Shear	Mohr-Coulomb	Always undrained	200	0.5	100

Table 4: Design wall shear resistance

- Increase the nodal density for the internal wall **Boundaries**. Click on each **Boundary** and in the **Property Editor** set the **Baseline Nodal Spacing** to 0.1 m. This will allow LimitState:GEO to more accurately model asymmetrical stress blocks on the internal wall **Boundary**. (Since the actual spacing is also affected by the choice of **Nodal Density**, it is good practice to check the actual spacing modelled using e.g. **Preview Nodes**. At least 8 blocks/9 nodes are recommended for the final analysis using e.g. a Fine nodal density (for initial checking of the model using a Coarse nodal density, use of this number of blocks is not necessarily essential).

Key modelling concept: *application of the adequacy factor in cantilever stem wall problems*

Deciding where to apply the **Adequacy factor** is a key stage in setting up any ultimate limit state analysis. Generally it should be applied to a unfavourable load or a combination of unfavourable loads that if increased would lead to the type of collapse being investigated. The question being asked of the software is 'by what factor do these parameters need to be multiplied by to cause collapse'.

Some loads might be favourable in certain failure modes and unfavourable in others e.g. in this example the weight of the block of backfill sitting above the wall heel is generally considered as favourable in a sliding failure mode but unfavourable in a mode involving bending failure of the wall stem. The **Adequacy factor** on the self-weight of this soil block should be set as *False* when checking against the former and as *True* when checking against the latter case. Otherwise the information about achieved margin of safety might be misleading. (Likewise the wall weight is favourable against sliding failure, but unfavourable against bearing capacity failure.)

Alternatively the **Adequacy factor** might be applied only on the surcharge load (as is done in this example). In this case, as explained in Step 6, LimitState:GEO will automatically inform the user if the loading type was incorrectly specified. If in the analysed problem there is no surcharge load, a low value dummy load might be used. Note that with this approach the structure is unsafe only if the result is *Unstable*. Any positive value of the **Adequacy factor** indicates that it is safe.

- 6) Specify the applied surcharge load of 10 kN/m^2 by selecting the relevant **Boundaries** and by using **Loads - Variable - Normal** via the **Property Editor**. Set the **Loading Type** for this to *Unfavourable*.

Note that the **Adequacy factor** for this variable load is by default initially set as *True*. This setting should be retained.

If an external load is initially set as *Unfavourable*, but it is actually *Favourable* in the failure mode returned by LimitState:GEO, a warning message will be displayed in the **Output** window. In such cases the analysis should be repeated with the **Loading Type** and the **Adequacy factor** settings for reported load changed to *Favourable* and *False* respectively. Note that LimitState:GEO assumes that a load specified on a **Boundary** arises from a single source and thus automatic verification of the **Loading Type** settings is performed only for the entire load on that **Boundary**. If load is not regarded as a single source and is expected to be neither entirely favourable nor unfavourable then the boundary on which load is applied can be divided using the **Draw/Vertex** or  function, and different settings applied to each part.

- 7) Set the **Loading type** of the **Solids** containing the *Granular Backfill* and *Stiff Clay* as *Unfavourable* in the **Property Editor**. The **Loading type** of the wall and of the **Solid** containing the *Loose sand* are set to *Neutral* by default. These could be changed to *Favourable* if required, though this is not strictly necessary since both normally attract the same partial factors.

These settings do not affect a Eurocode 7 DA1/2 analysis (where factors on permanent actions are always 1.0) but are relevant for a Eurocode 7 DA1/1 analysis. In this case they are appropriate for checking against structural failure in the wall. Note that following an analysis, the specified **Loading types** should be verified against the identified critical failure mode.

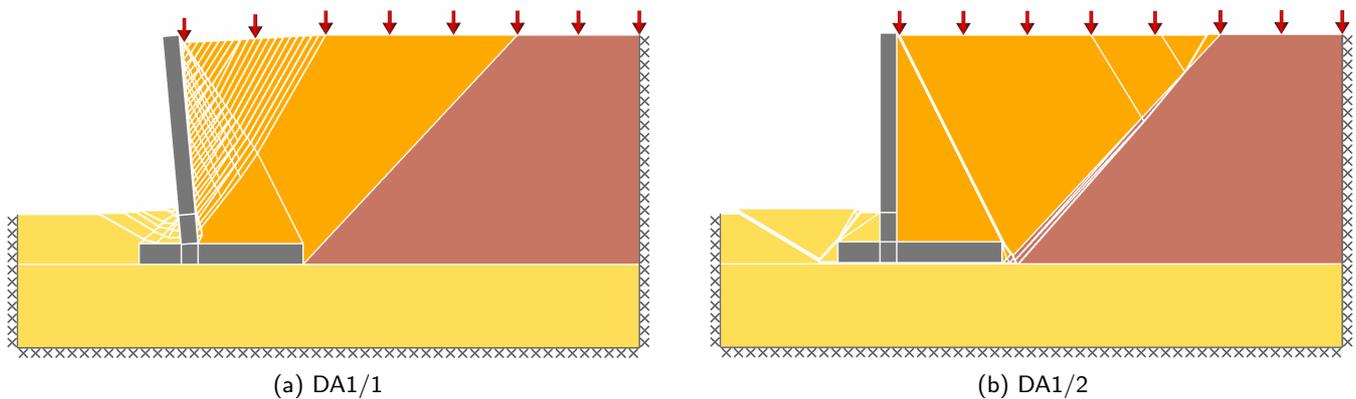


Figure 3: Failure mechanisms for the problem

- 8) Set the boundary conditions on the base and sides of the model as **Fixed**.
- 9) Choose the required Partial factor sets using **Scenario Manager**. In this example the Eurocode 7 Design Approach 1, Combinations 1 and 2 (DA1/1 and DA1/2) for long term analysis will be investigated. Select **Multiple scenarios** and choose DA1/1 and DA1/2 from the drop down boxes. Also in both scenarios tick the **Long term analysis** box to specify a drained analysis.
- 10) Set the **Nodal Density** to **Fine**.

4 Problem Analysis

The LimitState:GEO model may be set up manually as described in Section 3. Alternatively the complete model may be loaded by opening the file [cantilever_wall.geo](#).

Click **Analysis/Solve** or to obtain **Adequacy Factors** of 1.709 and 1.140 respectively for DA1/1 and DA1/2 scenarios. Both values are above 1.0 which means that in Eurocode 7 terms the design is safe. The additional margin of safety (or overdesign factor) in the critical scenario DA1/2 of 1.140 is given in terms of the load to which the **Adequacy Factor** was assigned.

Note that the Eurocode 7 DA1/1 analysis is carried out with factors on actions applied at source (e.g. soil self weight) by LimitState:GEO. Alternatively the method with factors applied on action effects i.e. actions as measured at the soil/wall surface might be used in the analysis. However in this specific case (where the backfill is cohesionless), the two approaches are essentially equivalent for the DA1/1 failure mode identified.

Also note that for the Eurocode 7 DA1/1 analysis approach the specified **Loading types** have to be verified against the critical failure mode found in the analysis as discussed in Step 7. In this case the specified **Loading types** were valid for the DA1/1 failure model identified.

If analysis results are required in terms of an alternative factor of safety (F.O.S.) such as factor on soil strength see the LimitState:GEO manual Section 8.2.3 and/or the Application Note: **Gabion Wall Analysis LS-G-AN2** for more information.

5 Frequently Asked Questions

- 1) *Why does LimitState:GEO provide only one failure mode and an associated Adequacy Factor whilst conventional limit equilibrium based software performs checks for several different standard failure modes?*

LimitState:GEO identifies the critical failure mode (which may not be a standard mode) from millions of potential mechanisms instead of checking a few pre-specified collapse modes. Thus only the critical solution is returned.

- 2) *LimitState:GEO returns an 'Unstable' result. What does this mean?*

The general answer to this question can be found in the **LimitState:GEO Help Pages** by clicking the hyperlinked text in the **Output** window if such result is returned. In the analysis of retaining structures a result *Unstable* will be returned if problem is unstable even if the load to which **Adequacy** is applied is removed (e.g. in this example, when wall collapses under the self weight of the *Granular Backfill* only, regardless of the value of the surcharge). In such a case the result *Unstable* means that either the structure or soil strength has to be increased.

- 3) *When considering a sliding failure mode LimitState:GEO identifies surcharge load directly above the wall heel as unfavourable but in the conventional analysis it would be treated as favourable. Why is this?*

This difference arises from the assumptions made in conventional limit equilibrium analysis methods where a virtual back is used and where a different collapse mode is assumed. To reproduce such conservative conditions in LimitState:GEO, a boundary with frictionless material representing a virtual back might be created.

- 4) *How accurate will the solution be?*

The accuracy of the solution depends on the resolution of the nodes at the failure mechanism. The accuracy can be refined either by increasing the **Nodal Density** or by optimizing the nodal distribution. For more information on how to improve solution accuracy see the LimitState:GEO manual Section 8.4.

- 5) *What is the purpose of the diagonal Boundary lines linking the points where the soil surface meets the stem and the ends of the wall base?*

Because LimitState:GEO models rotations only at boundaries, provision of these lines allows the enclosed triangle of soil to rotate as if part of the wall if required. Otherwise unnecessary additional shearing against the wall would be modelled. For further information please refer to the LimitState:GEO manual Section 5.3.3.

For more information: www.limitstate.com/geo