Workshop "Stability of Drystone Retaining Walls"

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Purpose of this workshop:

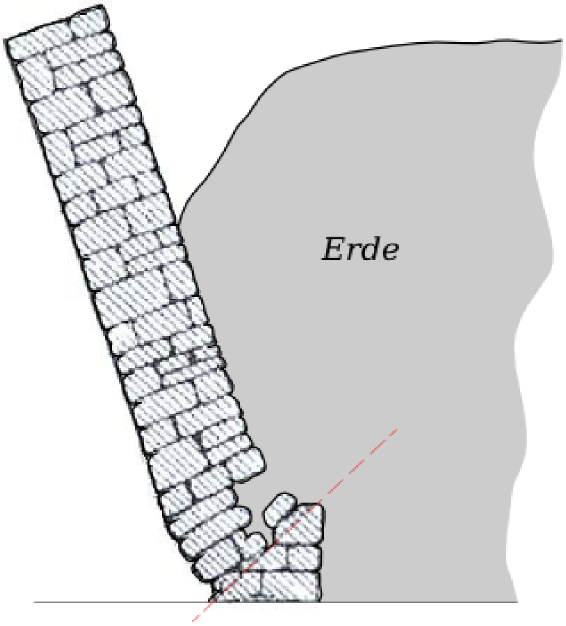
- Information for all interested persons
- Specific know-how for planners and builders
- Use of MurCalc retaining wall software.

Retaining walls can be calculated relatively accurately and optimised to use a minimum amount of stone while achieving defined margins of safety and a desired lifetime or suitability. In contrast, free standing walls or revetement walls cannot really be calculated. The latter look like retaining walls but are not subjected to earth pressure and can be as thin as practice allows.

The first task for calculating retaining walls is to determine the properties of the soil being retained, as the job of such a wall is to counteract with its weight the force of earth pressure.

A retaining wall is more likely to fail if it is built on soft ground. Often it is assumed that the ground supporting the foundation is sufficiently firm. Indeed the method of equilibrium analysis described below assumes theoretically infinitely firm materials for both wall and supporting ground. This model is sufficiently exact for most drystone walls built to the normal standards of experienced wallers, as they will make sure to place the foundation stones on firm ground, extend the foundation stones at the wall's toe, or replace the soft soil with compacted, firm material.

A retaining wall can be tipped over by excessive earth pressure relative to its thickness. A monolithic wall will then rotate forwards around a pivot formed by its toe. This is easy to calculate and is the basis of the standard procedure of equilibrium analysis. A drystone wall will generally separate in a region a bit further up, e.g. at the joint between the foundation stones and the first layer. This behaviour is more complicated and less well defined, but it is still possible to model it with sufficient accuracy.



Drawing of one of Sir John Burgoyne's famous research walls at the moment it is tipping over due to increasing earth pressure.

A wide retaining wall may alternatively be pushed outwards in a sliding movement without tipping. A monolithic wall will slide along the interface between its lower surface and the ground. A drystone wall will either do the same, or separate between stones inside the wall further up, whichever friction is lower.

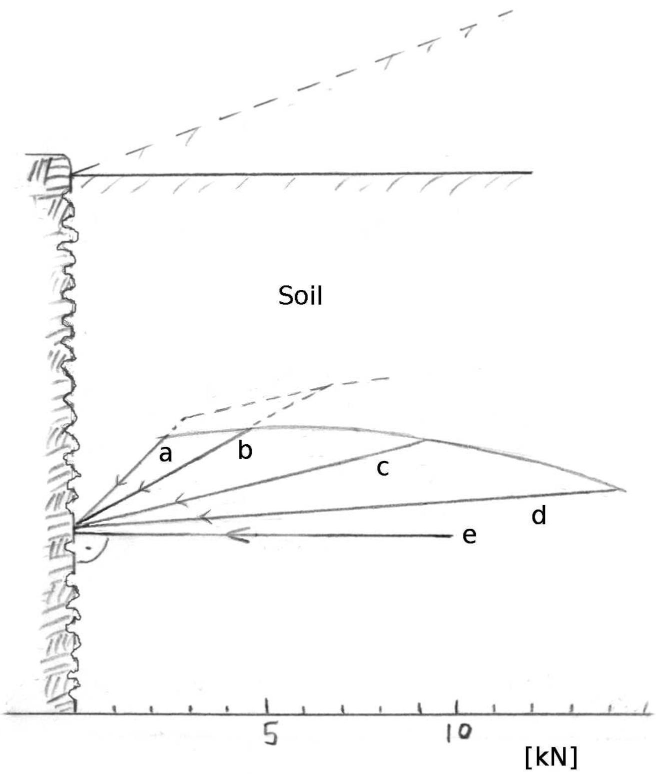
The first task is to determine the force from the so-called earth pressure. A more correct name would be soil stress, as it has a direction. Only liquids like water or very runny mud exert true hydrostatic pressure. At a given point, this is equal in all directions, thus pressing at right angles onto any surface at this point. At the other extreme, fully firm soil is a solid and presses only downwards in the direction of gravity. The force on the wall is either zero or easy to calculate, e.g. in the case of a wedge acting on the inner surface of the wall. Such soil is said to be highly cohesive.

The very fine particles of clay or silt stick together; this is called cohesion and is very dependent on the moisture content of the soil. As this property is difficult to measure, varies a great deal and is limited, it is usually ignored in calculations, However in practice cohesive soils are very important and facilitate building, as a bank will stay in place while the retaining wall is built against it. However cohesive soil as backfill also results in the eventual distortion or even distruction of almost any wall in the long run. This is because such soil will expand and contract with variations in water content or frost and millimeter for millimeter push parts of the wall outwards, in years, decades or centuries.

In order to avoid this and also give more exact calculations, non-cohesive soil can be used or assumed. This is granular material which is course-grained, e.g. gravel or cobbles. Sand is non-cohesive when dry but shows apparent cohesion when damp, as everybody knows who has ever made a sand castle on the beach..

All soils have two important properties: specific weight and internal friction. The latter is usually described as an angle of friction and called φ (phi). For non-cohesive material only, φ can be approximately visualised and measured by forming a fresh heap or bank. This forms an angle of repose, which approximates φ. Alternatively φ can be measured more accurately at the same time as any cohesion using special laboratory equipment. The higher φ is, the more stable the soil and the smaller the lateral earth pressure. The limit for loose soil is about 45° for very sharply broken or rough grains. Most materials are somewhat below this. For compacted soil it can be a bit higher.

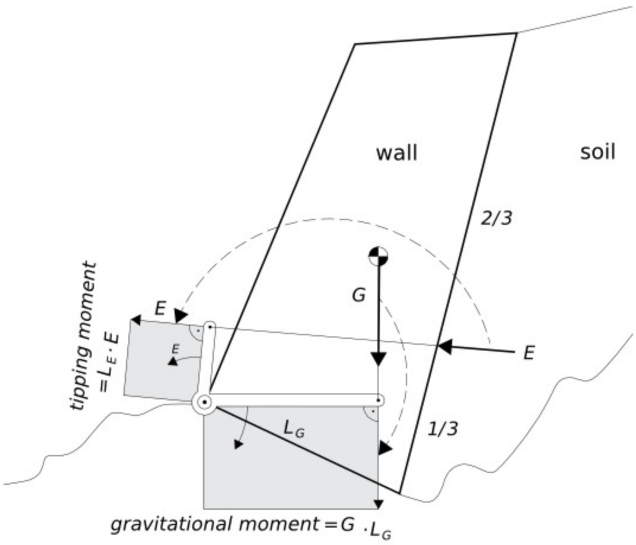
Another needed value is the friction angle between the soil and the wall's inner surface. This is called δ (delta) and is equal to φ for drystone walls with very rough inner surfaces. For normally rough surfaces, e.g. dressed stone, 2/3 φ is assumed and for normally smooth surfaces, e.g. cement walls, 1/3 φ is used. For liquids, δ is zero. δ determines the direction of the earth pressure force.



"Coulomb" earth pressure force in kilonewton per meter wall length, if the wall is 1.414 m high and the bulk weight of the soil is 18 kN/m³, for horizontal terraces (or 20°, dotted). The vectors a,b,c,d,and e are for friction angles (δ = φ) of 45° (sharp gravel), 30° (loose sand), 15° (highly unstable earth), 5° (highly liquified mud), and 0° (water).

If this and the specific weight and the internal friction angle φ of the soil is known, and also the slope angle of the retained terrace, an equation first developed by the famous French physicist Coulomb gives a coefficient describing the ratio between downward earth pressure, i.e. weight, and lateral earth pressure. It is often around 0.5 to 0.75. Thus the magnitude and the direction of the earth pressure force is known. In homogenous conditions it can be thought of as concentrated at a point one third from the bottom of the inner surface. An additional force in the same direction but thought of as being applied halfway up, is given by any surcharge on the terrace, such as people or vehicles.

Depending on the direction of these forces, the geometry of the wall profile and the friction, a wall can sometimes be infinitely stable, i.e. not overturnable or slidable by any force, no matter how large, only pushed ever more into the ground. This is however usually not the case and the wall's own weight is needed to combat the earth pressure, rather like a balance with the weight on one arm and the earth pressure force on the other.



A retaining wall on hard ground can be represented as a (L-shaped) balance between two moments or torques around the pivot formed by the toe. The wall will rotate around its toe if the earth pressure moment ist larger than the gravitational moment.

The wall's weight can be estimated or a sample measured and it is a straight-forward calculation to see whether this stabilising force or the destablising earth pressure force is the stronger. The calculation shows the factor by which the weight is stronger (or weaker) than the forces attempting to slide or tip over the wall. This is called the safety factor SF. A SF below 1 in sliding or tipping means the wall will fail by sliding or tipping. If it is 1, it is on the verge of failure, and anything above 1 shows that there is a margin of safety. Usual SF-values are 1.5 (50% margin of safety) but can be as low as 1.2 or required to be as high as 3. Values above this are fine but mean that more stone is used than required purely to insure stability.

Here follow various methods or tools for planners and builders in order to plan, assess or design a retaining wall.

Rule of thumb

The simplest method is the rule of thumb as used for free-standing walls: make the base width half the height and use some batter, e.g. 10-20%. This works surprising well also for usual retaining wall situations. If the soil is exceptionally stable, e.g. with a φ of over 40°, the width can be reduced to one third the height. If the soil is poor, e.g. with a φ of under 30°, or could become so with the influx of water, or appreciable surcharges are expected, the width should be increased to two thirds the height.

These rules suffice for walls where a failure would not cause injury and small projects where the amount of stone use is not of major importance. If however it is desired to use the least amount of stone in order to achieve a desired stabilty, one of the following tools should be used.

ENTPE-CAPEB

The book "Pierre sèche: guide de bonnes pratiques" (2008) published by the French organisation CAPEB (Confédération de l'Artisanat et des Petites Enterprises du Bâtiment) is based on work by the ENTPE (École Nationale des Travaux Publics de l'État) near Lyon, which was validated by testing and measuring to destruction full-sized walls built by local walling associations, the Muraillers de Provence and the ABPS. It is the monolithic equilibrium analysis described above but modified in order to model somewhat better the actual failure mechanism of drystone walls, which can break along a forward-slanted surface in the lower part of the wall. These results are given in the form of easy-to-use diagrams. The choice of profiles is limited to upright rectangles and trapezoids with a choice of two values of batter, two stone types and two terrace slopes in addition to horizontal. A single soil weight is assumed but φ can be chosen from zero to 50°, which is also used as the friction angle δ between the inner surface and the backfill. No surcharge is assumed and safety values of 1.2 and 1.5 are used, for sliding and tipping, respectively.
The same diagrams and much of the practical information is given in a much expanded English version (Drystone Retaining Walls, McCombie, Morel et al., 2016) in a collaboration between the Universities of Bath and the ENTPE.

FLL

The publication "Empfehlungen für Planung, Bau und Instandhaltung von Trockenmauern" (2012) by the German organisation FLL (Forschungsgesellschaft Landschaftsentwicklung Landschaftsbau) also provides easy-to-use diagrams and uses a simplified version of the monolithic equilibrium analysis and a few assumptions in order to change the results to values typical for drystone walls. There is a choice of several upright or tiltable rectangular and trapeziodal profiles, two stone weights and two terrace slopes in addition to horizontal. A single soil weight is assumed and φ can be chosen from 25° to 40°. The friction angle between the inner surface and the backfill is assumed to be δ = 2/3 φ. A surcharge of 5 kN/m² is always assumed. Safety values of 1.5 and up to about 3 are used, for sliding and tipping, respectively. An English version of the booklet is also available as PDF.

MurCalc

More powerful and universal than the preceding is my software MurCalc, written in the form of a spreadsheet. The present version 0.7 (2016) offers as profiles rectangles, CAPEB-type trapezoids, FLL-type trapezoids and the often-used chordal quadrilateral. They are tiltable (batter) to any degree but unfortunately only the rectangle offers a non-vertical inner wall.

Spreadsheet for calculating earth pressure force, sliding and tipping values of retaining wall profiles.

	Enter variables here						
profile type =	2	---->	1, 2, 3, or 4: means:	**chordal quadrilateral**	definitions see Info		
height =	1.50	m	definition see info	1.66	retaining height		
width =	0.80	m	definition see info	0.80	width at toe (m)	0.50	cope width (m)
batter =	20	%	batter of front face	0.30	absolute batter (m)		
β =	0	°	slope of retained terrace				
φ soil =	30	°	factor δ / φ = 0.99	29.70	δ (angle in ° from Eag to right angle on α)		
φ foundation =	30	°	angle of friction of foundation to soil	0.58	coefficient of friction μ of foundation to soil		
γ wall =	20	kN/m³	wall porosity = 25 %	26.67	specific gravity γ of stone (kN/m³)		
γ soil =	18	kN/m³	specific gravity of soil	1.11	ratio γ wall / γ soil		
p =	5	kN/m²	assumed load on terrace (actual or e.g. 5 kN/m² for people, 10 kN/m² for vehicles).				

974	α_L	11.31	°	inclination of foundation and stone layers			
	α	0.00	°	angle of inner surface to vertical			
	A	**1.04**	m²	area of profile	lever (m)	moment (kNm)	
	G	**20.78**	kN/m	weight per m length	0.469	9.75	stabilising moment (approximation with very small error)

active earth pressure coeff.	
Ka	**0.297**
Kah	**0.258**

earth pressure (kN/m²)	
eagh	7.71
eagv	4.40
eaph	1.29
eapv	0.74

earth pressure force (kN/m)		lever (m)	moment (kNm)	dist. toe (m)
		0.891	(Ld)	
Eag	**-7.37**	-0.055	0.40	
Eap	**-2.47**	0.264	-0.65	
		sum g	10.15	**0.416**
		sum g+p	9.50	**0.370**
Eagh	-6.40	0.393	-2.52	
Eagv	3.65	0.800	2.92	
Eaph	-2.14	0.670	-1.43	
Eapv	1.22	0.800	0.98	
sum g	24.43		10.15	
sum g+p	25.65		9.70	

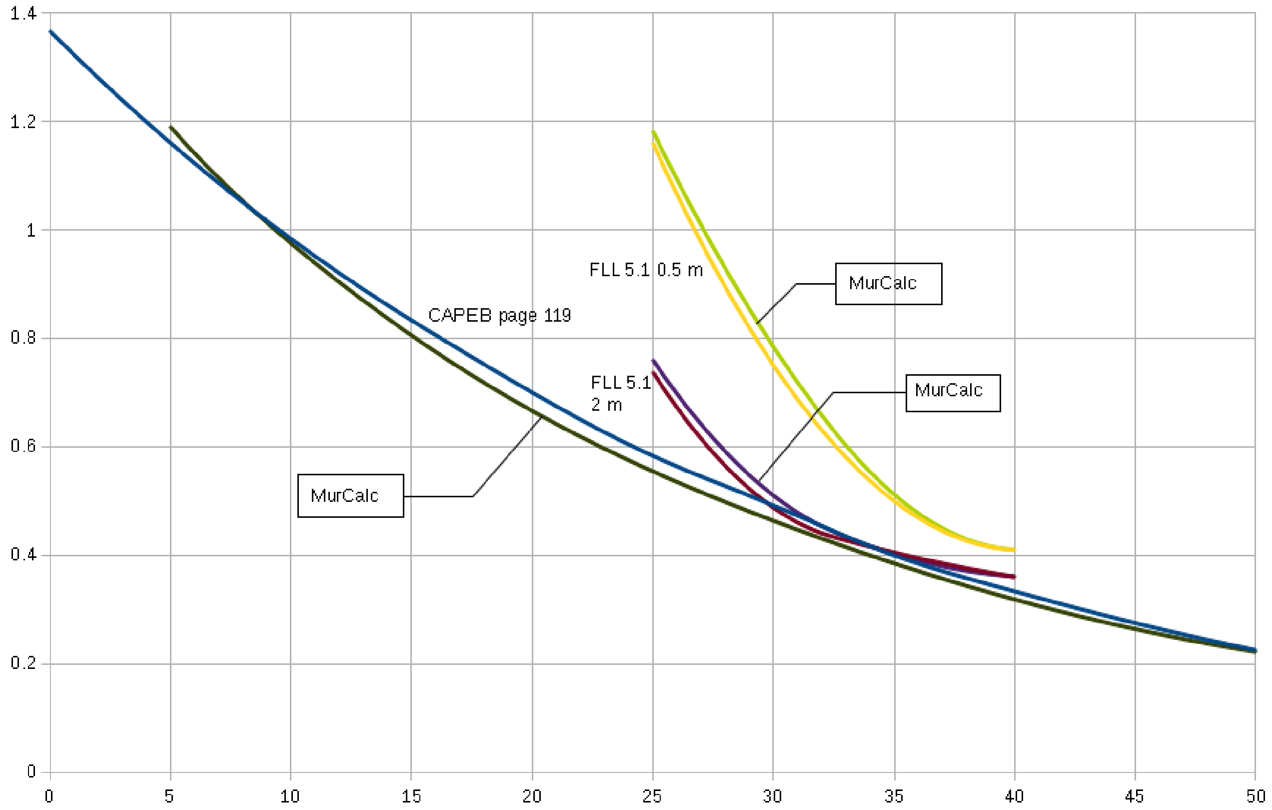
safety factor SF tipping	safety factor SF sliding
24.20	**9.813**
39.42	**4.632**

eccentricity e (m)

actual	max. allowed DIN	max. allowed SIA
-0.016	0.133	0.267
0.022	0.267	0.267

Any stone and soil weights and friction values can be specified, also any φ/δ ratio - representing friction between inner wall surface and soil, as well as any terrace slope (which must be less than φ to have any meaning). In contrast to the tools given above, the base width is an input, not a result. MurCalc does not assume any safety factors but rather gives these separately as a resulting function of the chosen input values. A small diagram representing the chosen profile and slope is also drawn.
The calculation is based on an almost exact monolithic equilibrium analysis. This can be used as is or adjusted in order to "simulate" either CAPEB- or FLL-

typical results. This means that an approximation of the ENTPE drystone-method is available over a wider range of inputs than offered by the CAPEB book. The degree of faithfulness is not known except for a few typical cases where it is quite good, as shown below.



Comparison of CAPEB and FLL wall examples and MurCalc simulations of these. The vertical axis represents the width-to-height-ratio, the horizontal axis the soil friction angle φ. It is seen that at φ = 30° all methods (CAPEB-wall any height, FLL-wall must be 2 m high) give about the same value of 0.5, which is also that given by the rule-of-thumb.

Disclaimer

All the tools given above come with no guarantee for correctness and have no legal standing e.g. instead of building codes. Walls of appreciable size, where a failure could lead to injury, should therefore also be checked by qualified persons. These might however use the same tools. In particular MurCalc is completely open and documented. The equations used are inside the cells but described in a more understandable manner in http://data.umwelteinsatz.ch/T/ (in German language, translation expeted in 2017).
In addition, profiles calculated with these tools will only perform as expected if the walls themselves are crafted to the normal standards of professional wallers or given in drystone walling literature or by drystone walling associations.