Design of Blockwork Walls

Conception des murs en blocs béton

C.T. Christensen & J.S. Steenfelt
COWI, Copenhagen, Denmark

ABSTRACT
A limit equilibrium method for determining the safety of blockwork walls has been developed and automated by means of an "intelligent" spreadsheet solution. Through the definition of a "virtual backface" and volumes of "backfill behind" the wall and "backfill carried" by the wall, the method takes into account the volume of backfill acting together with the wall, and thus considers the typical irregular backface of such walls, as well as individual block dimensions. The method cannot replace detailed analysis of displacements and settlements when such are needed, e.g. by finite element analysis, but the method represents a rational and cost-effective limit equilibrium tool for design - or design check - of blockwork walls and conventional cantilever type retaining walls.

RÉSUMÉ
Une méthode de détermination de limite à l'équilibre de la stabilité des murs en bloc béton a été développée et transcrite en une feuille de calcul. En définissant une "face arrière virtuelle" et des volumes de "remblai en face arrière" du mur et le "remblai supportés" par le mur, la méthode prend en compte le volume de remblais agissant en un ensemble avec le mur, et prend en compte l'irrégularité caractéristique de la face arrière de ce type de murs, ainsi que les dimensions particulière de chaque bloc. La méthode ne saurait remplacer une analyse détaillée des déplacements et tassements lorsque ceux-ci sont requis, déterminés par exemple par une étude à éléments finis, mais reste certainement un outil d'étude d'état limite à l'équilibre rationnel et rentable pour le dimensionnement - ou de vérification - des murs en blocs et des murs de soutènement conventionnel de type cantilever.

Keywords : Blockwork, Quay, Wall, Blockwall

1 INTRODUCTION

A limit equilibrium method for determining the safety of blockwork walls has been developed into a spreadsheet. The method takes into account the typical irregular backface of blockwork walls, by defining an evened out "virtual backface" against which active earth and water pressures act. The backfill volume between the real irregular backface and the virtual backface is considered part of the wall itself, see Figure 1. Down through the blockwork wall, earth and water pressures are accumulated together with self weights and possible seismic inertia forces, in order to track the resulting load transfer between blocks and onto the foundation base.

Blockwork walls are typically backfilled upon construction. Behind each block, the soil between the block and a possible user defined virtual backface, is defined as a volume of "backfill behind" in order to include possible seismic inertia forces from that soil volume onto the block in front. Similarly, soil directly above a block, but still below the virtual backface, is defined as "backfill carried" by that block, in order to take into account the stabilising dead load of backfill, see Figure 2.

For each block joint, the sliding and overturning safety, the contact pressure and the eccentricity of the load resultant are all checked. For the base block, also the foundation bearing capacity is checked, both considering a possible gravel pad and the underlying natural ground. Illustrative plots are made of the blockwork wall, the loads, the earth and water pressures acting upon it, and the resultants of load transfer between blocks.

Except for an in-situ cast capping beam, blocks are frequently mass concrete blocks (no reinforcement). A check on the shear and bending moment loading versus capacity of blocks are carried out, particularly for the base block, which often has a cantilevered toe and heel.

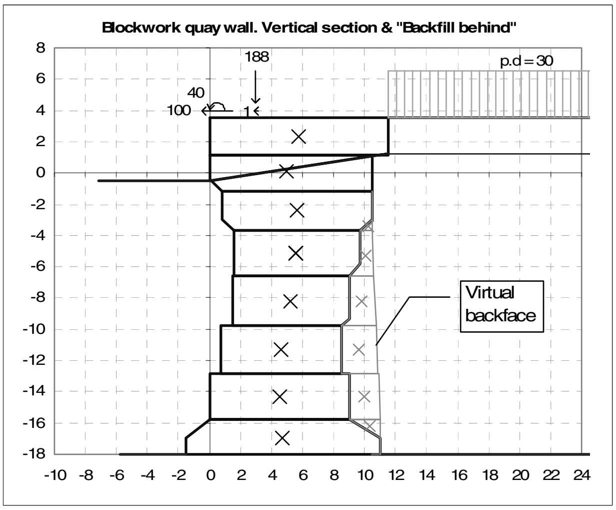

Figure 1. Blockwork quay wall & "backfill behind"

The definition of a reasonable virtual backface, as well as the roughness of the virtual backface, is left to the user of the spreadsheet. The user can assume any virtual backface, e.g. either vertical or inclined from the heel of the wall. Vertical virtual backfaces permitting the development of full active Rankine zones between the blockwork wall and the virtual backface should be defined with zero roughness, a point, which apparently has been missed in BS 6349:Part 2:1988 (Figure 35).

The spreadsheet is an in-house proprietary program of COWI. It is tailored for COWI's purposes and typical requests by COWI's Middle East Clients. The spreadsheet is not for sale.

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Commercial software exists for the same type of problems, e.g. the Czech (FINE Civil Engineering Software GEO5, 2007), and the "prefab wall" software of that package.

2 MODELLING BLOCKWORK WALL GEOMETRY

The modeling of a typical blockwork quay wall has been illustrated in Figure 1. A virtual backface has been defined behind the lower 6 courses of blocks. Each block and corresponding volume of "backfill behind" has been defined as a polygon, by entering the coordinates to the corners of the polygon.

The same virtual backface together with vertical lines from the backface of blocks have been used to define volumes of "backfill carried". The heel of the base block carries most of the backfill stabilizing the wall.

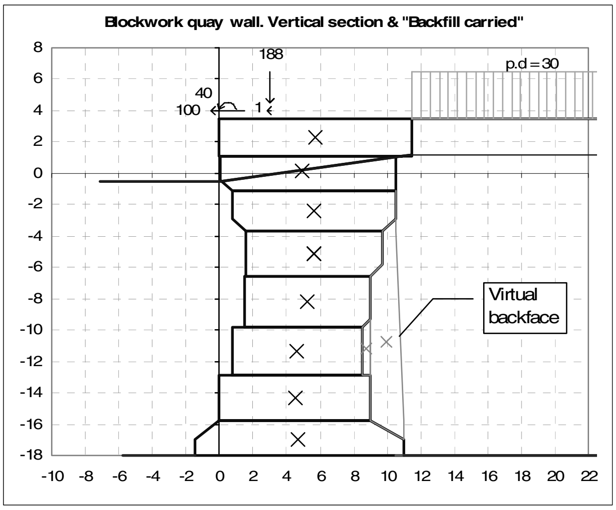

Figure 2. Blockwork quay wall & "backfill carried"

The methodology of defining wall and backfill soil is equally applicable for the design of conventional cantilever walls, cf. the example in Figure 3.

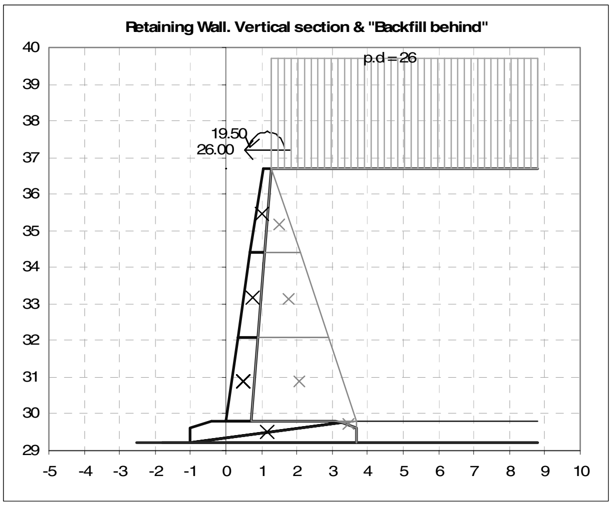

Figure 3. Cantilever retaining wall & "backfill behind"

3 AREAS AND CENTROIDS OF POLYGONS

Having defined the courses of blocks and the volumes of "backfill behind" and "backfill carried" as polygons with N corner points, (x_i, z_i), $i = 1..N+1$, where $(x_{N+1}, z_{N+1}) = (x_1, z_1)$, then the area, A, and centroid, (x_{CG}, z_{CG}), of each polygon may easily be calculated according to:

$$A = \frac{1}{2}\sum_{i=1}^{N}\left(x_i z_{i+1} - x_{i+1} z_i\right)$$

$$x_{CG} = \frac{1}{6A}\sum_{i=1}^{N}\left(x_i + x_{i+1}\right)\left(x_i z_{i+1} - x_{i+1} z_i\right)$$

$$z_{CG} = \frac{1}{6A}\sum_{i=1}^{N}\left(z_i + z_{i+1}\right)\left(x_i z_{i+1} - x_{i+1} z_i\right)$$

4 SAFETY

The safety of the structure is determined either according to a partial factor of safety concept, e.g. as in Eurocode 7 (2004) and Eurocode 8 (2004), or according to a total factor of safety concept.

5 STRENGTH PROPERTIES

Concrete and soil properties needed as input data are:

- Unit weights, γ
- Mohr-Coulomb strength properties, i.e. effective cohesions, c', and effective friction angles, φ'.
- Interface friction angles, δ'

6 LOADS

6.1 *External loads*

External loading in the form of a uniform surcharge, p, on the backfill may be entered.

Mooring loads, crane rail loads etc. may be entered as sets of vertical, horizontal and overturning moment line loads, F_v and F_h (both [Force/Length]), and M ([ForceLength/Length]), all acting upon the top face of the wall capping or the backfill made ground, in each of three vertical lines. All such external line loads are transferred to the capping, except the backmost vertical line load, when acting on the backfill. This is used to calculate an additional active earth pressure on the wall, e.g. in case of a crane rail founded in the backfill.

6.2 *Dead loads of wall and soil*

The dead loads of wall blocks and volumes of "backfill behind" and "backfill carried", per unit length of wall, are easily calculated, multiplying relevant polygon areas with respective unit weights.

6.3 *Seismic loading*

Effects of seismic loading are taken into account using the simple "pseudostatic approach". Horizontal and vertical seismic coefficients, a_h and a_v, are input.

All concrete block polygons involved in the wall are assumed acted upon by vertical and horizontal inertia force components proportional to their mass and a_v and a_h.

All "backfill behind" polygons are assumed acted upon by a horizontal inertia force proportional to their mass and a_h. This horizontal force is transferred to the wall block directly in front.

All "backfill carried" polygons are assumed acted upon by a vertical inertia force proportional to their mass and a_v. This vertical force is carried by the wall block directly below.

6.4 *Active earth pressure*

For concrete wall blocks, without definition of "backfill behind" and a virtual backface, the (inclined) active earth pressure acts directly against the backface of the blocks.

For wall blocks, behind which a polygon of "backfill behind" indeed has been defined, the (inclined) active earth pressure acts against the backface of the "backfill behind" polygon, considered as a "virtual backface". The "backfill behind" effectively becomes part of the wall.

The earth pressure, $E = 0.5\gamma KH^2$, is defined through the general Mononobe-Okabe earth pressure coefficient, *K*. Reference is made to either Eurocode 8 (2004), Part V, Annex E, or Indian standard IS 1893 (1984), Section 8.1.1, or the OCDI Japanese standard (2002), section 14.3. See also Figure 4 for a definition of terms defining *K*.

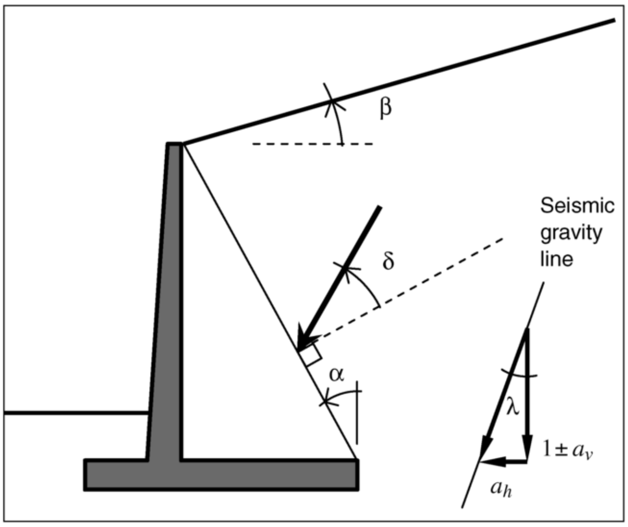

Figure 4. Angle definitions for Mononobe-Okabe earth pressure coefficient

For $\beta \leq \varphi\text{-}\lambda$ (i.e. when the backfill inclination angle, β, is less than the backfill friction angle, φ, minus the leaning angle of seismic gravity lines, λ):

$$K = (1 \pm a_v) \times \frac{\cos^2(\varphi - \lambda - \alpha)}{\cos(\lambda)\cos^2(\alpha)\cos(\delta + \alpha + \lambda)\left(1 + \sqrt{\dfrac{\sin(\varphi + \delta)\sin(\varphi - \beta - \lambda)}{\cos(\alpha - \beta)\cos(\delta + \alpha + \lambda)}}\right)^2}$$

in which the "+/-" that produces the greater active *K* shall apply.

For $\beta > \varphi\text{-}\lambda$:

$$K = (1 \pm a_v)\frac{\cos^2(\varphi - \lambda - \alpha)}{\cos(\lambda)\cos^2(\alpha)\cos(\delta + \alpha + \lambda)}$$

in which, again, the +/- that produces the greater active *K* shall apply.

6.5 *Interface friction angle, vertical/inclined virtual backface*

By reference to Figure 5 and assuming active earth pressures (wall moving to the left):

- For inclined virtual backfaces, extending from the back of the capping down to the back of the base block, cf. lower 2 sketches of Figure 5, shear will occur along the virtual backface and an interface friction angle, δ' = φ', is a reasonable choice.
- For vertical virtual backfaces, from the base block backface up, and with level backfill, and when the geometry of the wall permits the development of a full active Rankine zone, cf. upper left hand sketch of Figure 5, the only reasonable interface friction angle to assume along the vertical virtual backface is δ' = 0.
- For vertical virtual backfaces, from the base block backface up, and when the geometry of the wall does not permit the development of a full active Rankine zone, cf. upper right hand sketch of Figure 5, the interface friction angle, δ', along the vertical virtual backface is in the range 0 < δ' < φ'. Selecting δ'=0 will be a safe selection.

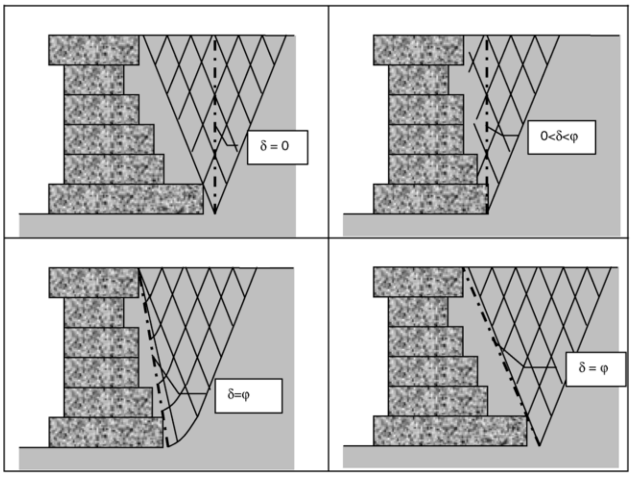

Figure 5. Shear along various virtual backfaces

Similar reasoning for selecting δ'=0 for vertical virtual backfaces and level backfill, β=0, can be found e.g. in Terzaghi et al. (1996), Section 45.4.3 and Figure 45.7.

The above reasoning for selecting the interface friction angle to be δ' = 0 along vertical virtual backfaces (at least for the case of level ground) appears to have been missed in BS 6349:Part 2, (1988), Figure 35.

6.6 *Differential water pressure*

The level of a possible free water surface in front of the wall and a possible groundwater table behind the wall may be defined as well as the assumed variation of these surfaces through the wall.

From the user defined free water and groundwater surfaces, the appropriate unit weights (total or buoyant) are applied when calculating total and buoyant weights of respective polygons, and the driving horizontal differential water pressure is determined.

6.7 *Additional seismically induced dynamic water pressures*

Additional reductions in the stabilizing water pressure in front of the wall as well as additional driving groundwater pressure behind the wall are included according to Eurocode 8 (2004).

7 RESULTS

Typical earth pressure plots of earth pressure due to soil self weight and possible seismic action are automatically generated, e.g. as illustrated in Figure 6.

Similar earth pressure plots of earth pressure due to uniform surcharge and possible soil cohesion are also automatically generated, e.g. as illustrated in Figure 7.

External loading, dead loads, differential water pressure, possible seismic loads and earth pressures are all accumulated down through the courses of blocks.

The resulting force transfer in each interface between wall blocks is automatically illustrated by plotting the resultant of the load transfer in the interface, see Figure 8.

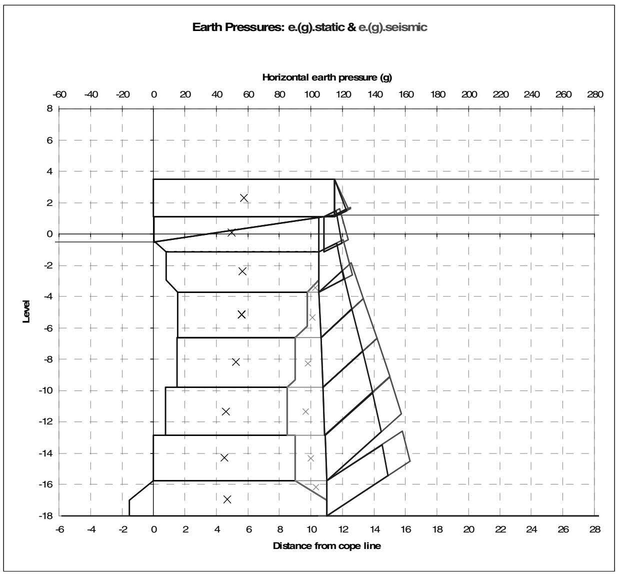

Figure 6. Active earth pressure due to soil self weight and possible seismic action

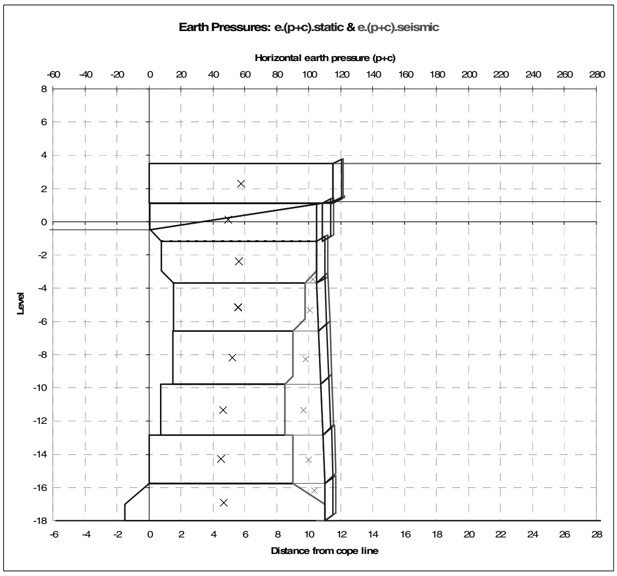

Figure 7. Active earth pressure due to uniform surcharge and possible soil cohesion

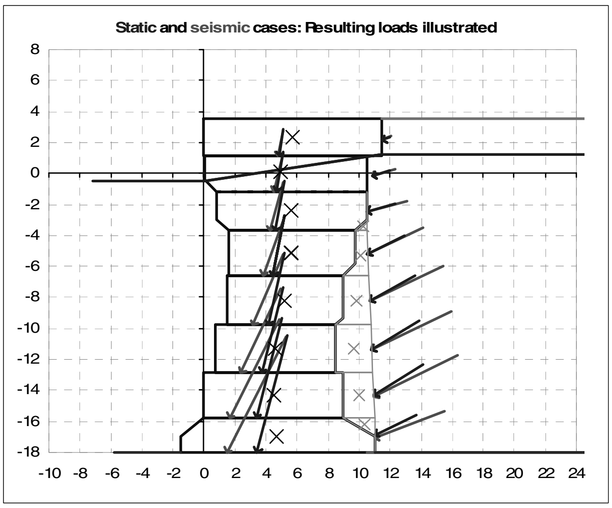

Figure 8. Resulting static (blue) and seismic (red) load transfer down through blockwork wall

8 BLOCK ROBUSTNESS

The robustness of all concrete blocks forming the blockwork wall is investigated by statically correct distribution of topside and downside load resultants, cf. Figure 8, and determination of internal bending and shear in blocks. From bending and shear, the magnitude of possible tensile stresses within each concrete block is determined.

The tensile stresses within each concrete block must be shown to be below a reasonable tensile stress criterion for tensile splitting or shearing of un-reinforced concrete.

Compressive stresses must of course also be verified to be within a reasonable compressive stress criterion, dependent on the concrete compressive strength.

9 CONCLUSIONS

A limit equilibrium method for determining the safety of blockwork walls has been developed and automated by means of an "intelligent" spreadsheet solution.

Smooth virtual backfaces are generally assumed, when full active Rankine zones are free to develop on either side of the virtual backface. The general interface friction along vertical virtual backfaces, $\delta' = \varphi'$, recommended by British Standard, BS 6349:Part 2, (1988), Figure 35, is "unsafe". Such should not be employed, when mentioned full active Rankine zones are free to develop, e.g. when block "B" in said BS Figure 35 has a relatively wide heel.

The spreadsheet has been developed to automatically investigate a series of static and seismic load combinations, including various water table assumptions. The outcome is tables of overall safety factors for bearing capacity and sliding of the entire wall on the foundation soil/rock as well as overturning and sliding in individual block joints. Maximum contact pressures and eccentricity of load resultants are also listed, and individual block robustness is checked.

The spreadsheet described and illustrated here has been used by COWI to design hundreds of kilometers of blockwork walls. Considerable time saving in design work has been achieved. Detailed design and optimization of a cross section can be made in less than one day, once all loads and load combinations have been defined.

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