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Innovative restoration of medieval city walls of 's-Hertogenbosch by soil nailing

Restauration des murs de la ville 's-Hertogenbosch par clouage

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ABSTRACT

The city of 's-Hertogenbosch initiated the restauration of the medieval city walls following the european regulations on the preservation of the historical and cultural heritage. For the repairworks are innovative techniques applied such as soil nailing for providing low impact in situ restauration in accordance to the Malta treaty from 1992. The objectives to be met in the restoration relates both the technical improvement of the walls as the unique vegatation and fauna living on the walls.

RÉSUMÉ

La ville mediévale de Bois le Duc aux Pays Bas avait décidé de restaurer les murs de soutènements qui servaient de rempart au moyen age. Ceci conforme aux normes Européennes en vigeur pour la conservation de l'héritage historique et culturel (accord de Malte 1992). Les solutions techniques utilisées pendant la restauration (clouage du sol derrière les ouvrages de soutènements, renforcement des fondations et réhabilitation de la maçonnerie) ont été conçues de telle façon quelles conservaient l'équilibre de l'environment en préservant la flore et la faune existantes sur le murs et aux environs.

1 HISTORY OF CITY WALLS

The city of 's-Hertogenbosch situated in south of The Netherlands has a rich history throughout the ages. Due to its strategic position in the area it has been inhabited by the Romans and further on through the Middle Ages until the modern times. The city is surrounded by a brickwork city wall. The wall was built already in Roman time and greatly extended in Middle Ages. From then on the wall was strengthened in every new era. This was done by new layers of brickwork, locally with buttresses and in later period also by making a supporting embankment behind the wall consisting of sand, clay and a waste material of antropogenic origin.

Figure 1.1 View at City wall

In a front of the wall is still present a defense ditch also the streambed of the river Dommel.

2 PRESENT SITUATION

The city of 's-Hertogenbosch has an unique place in the Netherlands because the ancient city walls which are not enclosed by the urbanization. The city walls that are to be restored are neighbouring freely with the grasslands (polders) at the other embankment of the Dommel river. Under these conditions has developed a unique ecosystem at the wall. The biologists, etymologists and other environmental experts has been concerned about the vegetation and fauna (a.e. bats) living on the walls. At the city side of the wall a busy road is situated. directly behind the wall. Occasionally is this divided from the wall by a narrow strip of green (2 to 6 m wide) with full grown trees.

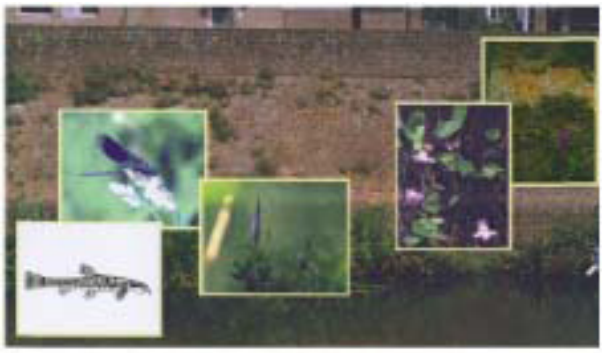


Figure 2.1 Ecology of the project

Municipality engineers inspected the walls and concluded that a great deal of the wall is currently showing a serious amount of decay on foundation and brickwork.

3 PRESERVATION OF THE HERITAGE

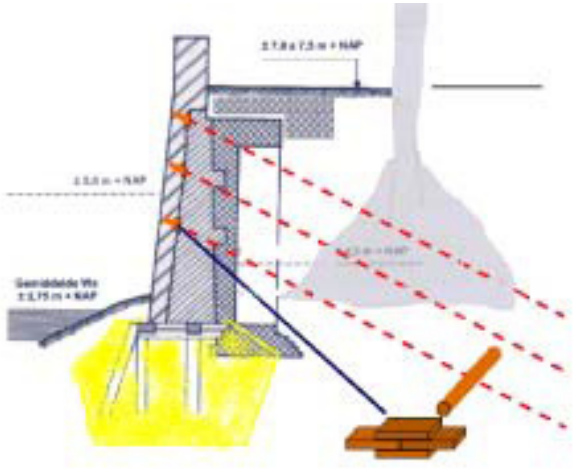
The city of 's-Hertogenbosch has decided to restore systematically the critical places of the complete city wall. With the encouragement by the legal system of the Netherlands that according the European treaty of Malta (1992), among others, obliges the preservation of the national heritage preferentially in situ. The financing of the project was possible with both the governmental restoration budget and subsidiaries of European Funds.

Figure 3.1 Situation of the city walls.

The goal of the restoration was the strengthening of the total brickwork wall without substantial replacement by new stones and at the same time to rearrange a durable foundation structure under the wall.

Furthermore an important condition for the restoration is to preserve the existing ecosystem and archeological values without interfering in the existing infrastructures (traffic and cable connections) as well as vegetation (tree roots) behind the wall.

The first two phases of the restoration concern 1 km of the wall from the Zuidwal to Spinhuiswal with the defence towers Grote Hekel, Bastion Oranje and Bastion Vugt.



3.2 Conditions and principal of the restoration

4 PROJECT BOUNDARY CONDITIONS

For the geotechnical analysis of the situation the CPT-logs and borings taken behind the wall were evaluated. This study had shown that anthropologic layer behind the wall varies in depth and thickness, as could be expected historically, consisting of deposits of sand, rubble and loam. Under the anthropologic sediment a sound sand is found approximately at NAP +1.0 m. The phreatic water level behind the wall lies at a level of approximately NAP +3.7 m. The lowest water level in the ditch in front of the wall stands at NAP +2,7 m, which leads to a water level difference of not more than 1 m behind and in a front of the wall.

The Catholic University of Leuven (KUL) performed a geophysical investigation on the thickness and the true condition of the mortar in the brickwork by borings in the wall performed at the several levels. The borings had shown the real thickness of the wall and very often the poor condition of the brickwork with gaps between several layers. The thickness of the wall varied from approximately 0.6 m at the top of the structure (NAP +7.0 m) and increased to 2 `a 3 m of thickness of the structure at the foot of the wall.

Figure 4.1 Drilling of the cors

Further investigation by means of trial pits had shown parts of the wall with a wooden pile foundation as well as parts of the wall with shallow foundations on the sand layer. There were great insecurities about homogeneity of the brickwork and the depth of the foundation (top of the pile foundations approximately at NAP +2.95 m and shallow foundation at NAP +1.0 m). The presence of the trees and cables behind the wall made a restoration with help of a auxiliary sheetpile behind the buttresses a non-desirable and technically not a feasible option.

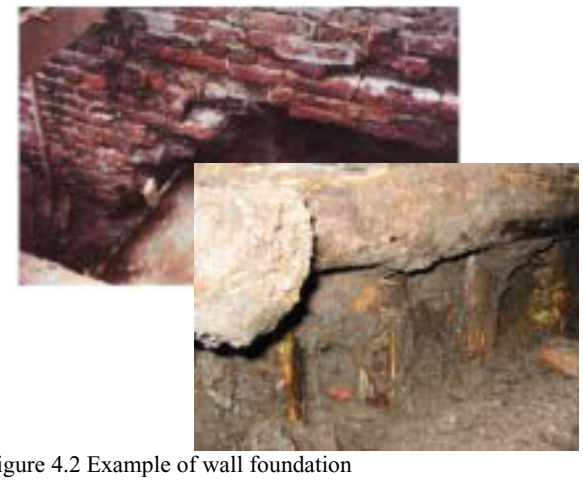


Figure 4.2 Example of wall foundation

5 FAILURE MECHANISMS

Beforehand to a choice of a restoration approach the possible failure mechanisms of the (gravity) wall has been considered. As design condition is taken into account the present condition of the wall during the excavation in front of the wall for the restoration of the foundation structure. The final situation after the reconstruction is assessed as well. The specific main failure mechanisms are considered as follows:

- sliding of the base of the wall over the underlying soil;
- overturning of the wall;
- deficiency of the bearing capacity of the underlying soil;
- development of the deep slip surface which envelopes the wall as a whole;
- a structural failure of the wall due to large soil and wall deformations;
- an internal erosion or leakage of the wall;
- a piping mechanism under the base of the wall.

A detailed investigation made clear that a failure due to the piping underneath the base of the wall could be neglected, because of the particle size distribution of the sand. The study of the mechanism based on the formula of Selmayer has shown that piping is not expected to occur. All other mechanisms have been investigated and proved likely to occur if no measures were taken.

STRUCTURAL ASSESSMENT

The structural assessment of the brickwork with the buttresses (by KUL) has shown that a part of the wall could be restored by means of injection (strengthening) of the wall and the anchoring of the buttresses being performed. This approach was possible under the condition that the brickwork between two buttresses has sufficient thickness and strength to allow development of the arching mechanism (as known from the roman and gothic ceilings and stone and brickwork bridges). A major part of the wall however was in such a bad condition that above mentioned restoration method was not possible. Instead thereof the soil nailing method was envisaged to take into account the brickwork's structure condition.

6 GEOTECHNICAL DESIGN OF SOIL NAILING

6.1 *General philosophy*

For the greatest part of the wall the analysis of possible risks leaded to an inventive choice of restoration by means of soil nailing. The philosophy on this approach has been the possibility to develop a self supporting mass of earth behind the wall without a prior need of strengthening of the weak unreachable brickwork parts that are mainly under the ground- and water level. The soil nailing results in decrease of the lateral pressure directly at the "back" of the weak masonry structure. To increase the friction between the nail and the soil, all nails are injected with cement holding substance. The chemical content of the injection mixture has been such that the ph grade of the masonry environment will not change.

6.2 *Soil nailing design*

The restoration case with soil nailing has been designed with the convenient tool of TALREN program, based on Bishop circular failure method. The design parameters for the calculation have been determined based on cone resistance and friction from the Cone penetration tests (CPT-test).

The design calculations are based on the "worst case scenario" defined by a realisation of the foundation improvement in excavation procedure with a limited width in front of the wall. Because of the presence of the nails behind the wall the mechanisms such as sliding or overturning of the wall are not critical any more. The chance of structural collapse of the wall due to a possible lack of the bearing capacity of the substrata is unlikely as proved by calculations. The occurrence of the slip circle as failure mechanism is however assumed to be leading for design of the soil nailing. The triangle pattern of 1.0 m x 1.5 m (HxV) of the steel nails with the length of 7 m behind the wall (with diameter of 0.025m) has been found optimal for the major part of the wall. Slight optimization was possible for different soil types behind the wall and different distance of the traffic load.

Design of soil nailed structure in sand is a more common type of the ground improvement. The design of the soil nailing in the cohesive soil is a less explored issue and requires denser pattern of the nailing points (increase of 15 to 40%).

Prediction of deformations of nailed soil and the masonry structure is globally done by FEM analysis program Plaxis. The predicted deformations have been in the range of 20 to 35 mm and the forces in the nails did not exceed 50 kN per nail (design value). Because of the insecurities about the strength of the masonry no detailed prediction has been performed and the budget cuts didn't allow a sound monitoring program to verify the predictions.

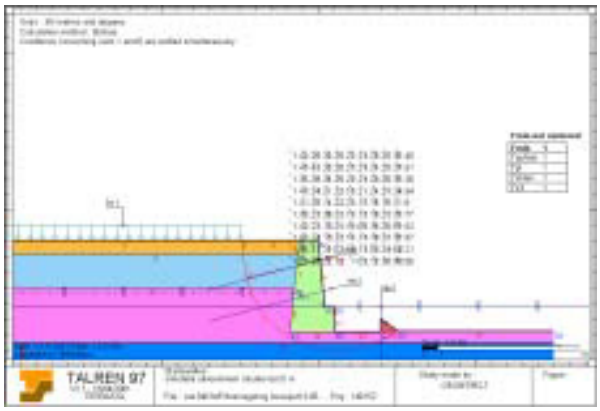


Figure 6.1 TALREN graphical output of the design calcualation

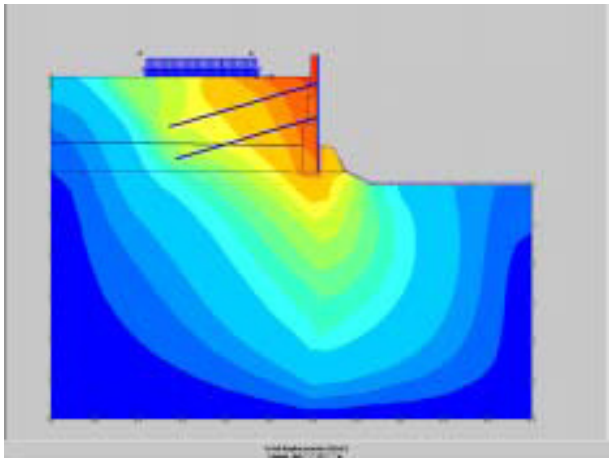


Figure 6.2 PLAXIS calculation

7 FINALIZING RESTORATION

Soil nailing protects the weak parts of the wall. The structural strength of the wall is regained by injection of mortar. The injection mixture is chosen such that this is not harmful to the vegetation.

Figure 7.1 Removal of the brickwork for the nailing

When the wall regains the structural strength, the restoration can be completed by foundation improvement. This is performed in restricted compartment sections of maximum 5 m. This is done with an auxiliary sheetpile construction (installed by pressing device) at the distance of approximately 2 m from the front of the wall. Within the sheetpile section soil is excavated under water with a slight over-cut up to the foundation level of the wall. In the over-cut and in de excavated space in the front of the wall is made a 0.8 m thick foundation plate by means of the pouring under water concrete. After hardening of the plate the space in the front of the wall pumped dry so the damaged parts of the brickwork could be replaced by new stones and mortar between the stones could be refreshed. After this procedure is the excavation backfilled and water level is brought in the original level. The auxiliary sheetpile is carefully pulled out after finishing of the works.

Figure 7.2 Installation of the high and low row of the nails

8 CONCLUSION

The chosen innovative approach of the city wall restoration with soil nailing gives possibility of low impact environmentally friendly, challenging engineering in urban areas.

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