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CIVIL AND ENVIRONMENTAL ENGINEERING REPORTS

E-ISSN 2450-8594

CEER 2020; 30 (1): 161-170
DOI: 10.2478/ceer-2020-0012
Original Research Article

NUMERICAL ANALYSIS OF STRUCTURAL AND MATERIAL SOLUTIONS FOR SELECTED RETAINING WALLS

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A b s t r a c t

Designing retaining structures depends on many factors, primarily the function of the retaining structure and soil conditions. It is not easy to choose the right retaining structure due to the great variety of their structural and material solutions. Preliminary numerical analyses in this case can be very useful. This article presents the results of numerical analyses of the behaviour of retaining structures and soil for various structural and material solutions as well as defined soil and water conditions. Six variants of retaining structures were analysed, in which the type of retaining walls, the materials used and the height of the walls were varied. The assessment was done basing on maps of stress and displacement of the retaining structure and soil. An additional factor in the selection of retaining structures are costs, durability and lead time. The finite element method allows the analysis of the behaviour of the structure - soil system. It enables comparison of various construction variants at the design stage and selection of the best solution in given soil and water conditions for the set selection criteria.

Keywords: retaining structures, numerical analysis, FEM

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1. INTRODUCTION

Retaining structures belong to one of the oldest and most important engineering structures. They constitute an artificial barrier against landslides from higher-level grounds. They are very important especially in infrastructure construction, as an element of bridge structures and a component of road investment. On a smaller scale, retaining structures are used in housing, when for various reasons smaller or larger ground faults should be secured. Currently, both geotechnics and detailed issues regarding the design of retaining structures are the subject of analyses of many engineers. They are looking for solutions that will allow them to thoroughly understand and effectively use the phenomena occurring in the soil - especially pressure and resistance - by including the ineraction beetwen soil and construction. At the same time, emphasis is placed on improving the shape of the structure through its optimization. It can be achieved by using more and more modern computer software. On the one hand, it allows to design a structure whose load capacity meets 85-95%. Thank to this, it is possible to save funds for additional reinforcement, making a thicker section, or adding another layer of geogrid. On the other hand, thanks to advanced computer systems, the previously dimensioned structure can be quickly checked and modified, which reduces the time necessary for the design process. In turn, conducting numerical analysis and modeling the soil-structures interaction makes possible to check and predict the behaviour of the system in reality.

2. STRUCTURAL AND MATERIAL SOLUTIONS FOR RETAINING WALLS

2.1. Types of retaining walls

The PN-EN 1997-1 [2] norm distinguishes three main types of retaining structures - these are gravity retaining walls, embedded walls and composite retaining structures.

Gravity retaining walls are structures made of stone of plain or unreinforced concrete. The weight of the wall itself plays a significant role in the support of the retained material (that is why they are called gravity walls). Examples of such walls include concrete gravity walls having constant or variable thickness, spread footing reinforced concrete walls and buttress walls. Embedded walls are relatively thin structures made of steel, reinforced concrete or wood, supported by anchorages, struts and/or passive earth pressure. The weight of such wall in this case is insignificant - the most important parameter is the bending capacity of the soil retaining elements. Examples of such walls include cantilever steel sheet pile walls or diaphragm walls. The last group of retaining structures mentioned in [3] are composite walls. In engineering practice, there are many examples of such walls and they are characterized by considerable diversity. Examples include double sheet pile wall cofferdams, small-scale system structures or earth structures reinforced by tendons, geotextiles or grouting.

2.2. Types of retaining structures, conditions for their use

According to the provisions of PN-EN 1997-1 [2], retaining structures are all types of walls and retaining systems such that their structural elements are subject to forces exerted by the retained material. Nowadays there many types of retaining structures. Their classification may be done according to the material used, method of work, type of load or production technology (Fig. 1).

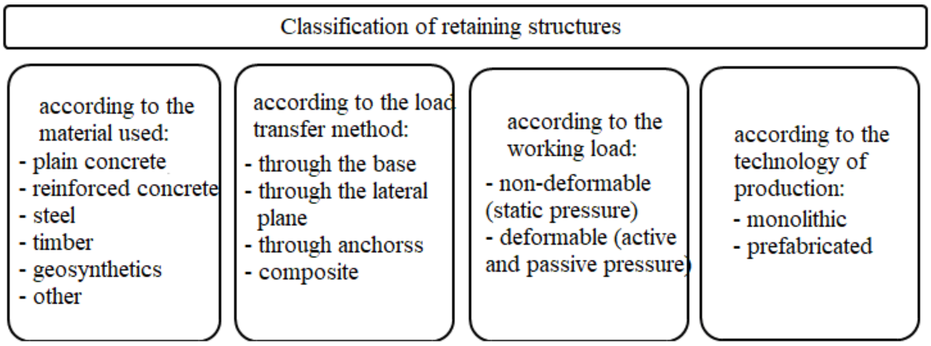

Fig.1. Types of retaining structures [2]

The retaining structures are usually made from reinforced concrete, steel, wood and various types of geosynthetic materials. Reinforced concrete structures can be in the form of prefabricated elements (Fig. 2) or they can be made on the construction site (Fig. 3).

Fig. 2. Prefabricated elements of a retaining wall [9]

Fig. 3. Monolithic retaining being built [10]

Steel is a very common material for making various types of retaining structures. It is mainly used to protect the walls of excavations, more often as a temporary solution than a permanent one. Steel sheet piles, i.e. rolled sections with a specific cross section and material and strength characteristics can be used as durable retaining structures (Fig. 4).

Fig. 4. Typical structures using Larssen sheet piles [11]

Wood is another material used to make retaining structures. Wooden gravity retaining walls are called caissons (Fig. 5).

Fig.5. Wooden retaining structure in the form of caissons [12]

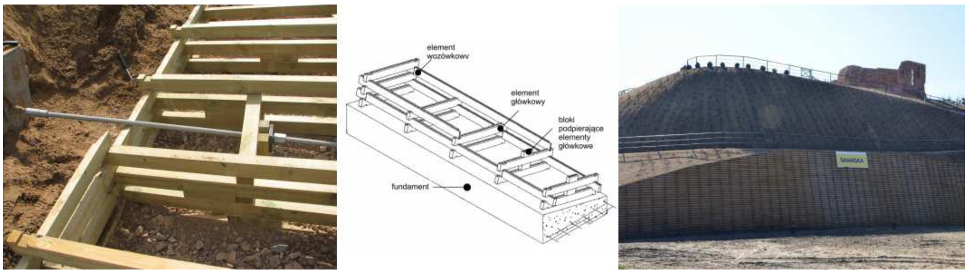

Fig. 6. Contemporary caissons [12]

Nowadays there are companies that make wooden retaining walls in the new technology (Fig. 6). These constructions have the form of boxes made of transverse (head) and longitudinal (cart) elements, joined together with carpentry connections.

One of the first materials used to make retaining structures was stone. With time, the technology of producing materials for pointing and joining elements developed and individual stones were joined with mortar (Fig. 7).

Fig. 7. Retaining structure of fieldstone [13]

Fig.8. Retaining structure of gabion baskets [14]

Currently resistance structures using gabions are very common (Fig. 8). Such elements can be used to strengthen slopes.
Geosynthetics are a completely different group of materials used in retaining structures. The idea of making walls from soil reinforced with geosynthetics was born in the 1960s by the French engineer Henri Vidal [5].

Fig.9. Retaining structure using geogrid [14]

Fig.10. Retaining structure using geotextile [15]

Reinforced soil constructions have found wide application, for example in transport and hydrotechnical construction. These types of structures use native soil, covered with layers, between which reinforcement elements are located. These can be geomeshes, geogrids and geotextiles (Fig. 9, 10).

3. ANALYSIS OF THE WORK OF SELECTED STRUCTURAL SOLUTIONS FOR RETAINING WALLS

3.1. Analysed retaining wall variants

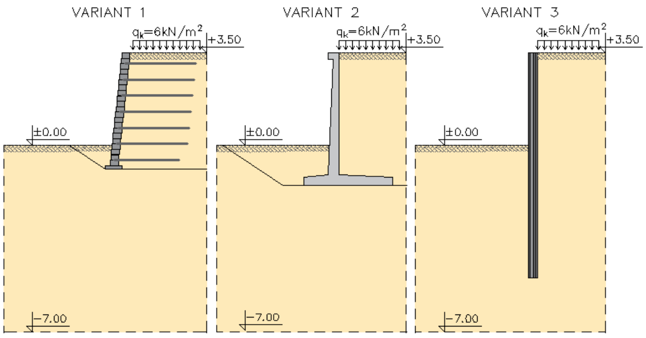

Fig. 11. Design variants 1, 2 and 3

The presented article examines the behaviour of three types of retaining structures. Each of them was considered in two heights: Δh=1.5m and Δh=3.5m. The considered variants of retaining walls are shown in Figures 12 and 13.

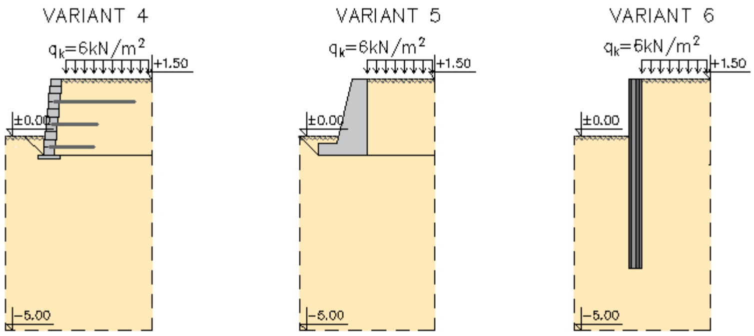

Fig. 12. Soil conditions for design variants no. 4, 5 and 6

The first structure tested (variant 1), illustrated in Fig. 11a, was designed as a retaining wall in the Allan Block system [8]. It is a solution that combines the advantages of geosynthetics as a material interacting with the soil and concrete blocks without mortar, which primarily perform the function of facing the whole wall. The geogrid connects the wall with the surrounding soil to form a structure that, thanks to its own weight and internal shear strength, can effectively resist slipping and rotation of the wall due to soil pressure. In this case, the wall of hollow blocks is also an aesthetic face of the structure.

The second analysed variant concerned a retaining structure made as a prefabricated spread footing reinforced concrete walls (Fig.11b). The third variant concerned a retaining structure in the form of a steel sheet pile (Fig. 11c). Retaining structures in variants 4, 5 and 6 were designed in a similar way (Fig. 12). They differ in height from previous variants; the first three variants are constructions with a height of 3.5m above ground level, while the second group consists of constructions with a height of 1.5m above ground level. For the difference in ground level of 1.5m, a gravity retaining wall was analysed.

3.2. Numerical models

All variants of retaining walls have been modelled in the Simulia Abaqus software [7]. A simplified calculation model consisting of solid type elements was adopted. The linear-elastic behaviour of individual materials was assumed. Contact conditions have been set expressed by the friction coefficient of individual system components in accordance with literature recommendations [16]. For example, for variants 1 and 4 (retaining wall in the Allan Block system) for the contact surface of concrete blocks it was assumed to be equal to 0.7, the contact surface of the block-grid was taken as 0.5, for the contact between the block and soil 0.4 for grid-ground contact - 0.3. A 5x5cm finite element mesh generated for the adopted soil block, 1x1cm for concrete blocks and 1x1mm for geogrid. The total number of finite elements in option 1 was 60344.

For variants 2 and 4, the adopted calculation model assumes a linear-elastic work of materials. Taking into account the contact at the construction-soil interface, a friction coefficient of 0.4 [15] was adopted. The finite element mesh for variant 2 consists of 48390 elements with dimensions of 5x5cm for the soil massif and 1x1cm for the structure.

In options 3 and 6, the simplification resulting from the use of 2D analysis is very large - instead of the actual cross-section of the AZ type, a 8.5mm thick flat bar is used. The actual cross-section has been taken into account by introducing the proper stiffness of the element. The model adopts linear-elastic material behaviour. Finite elements 5x5cm were assumed for the soil massif, and 1x1mm for the sheet pile. The model was divided into 34401 elements of the ES grid.

3.3. Obtained results

As a result of numerical analyses, maps of reduced stress in the retaining structure and soil as well as horizontal and vertical displacements of the retaining wall-soil system were obtained. Fig. 13 shows the stress and displacement distribution for a system with a gravity retaining wall (option 5). Obtained results in the field of displacements and reduced stresses can be regarded with some reservations as an approximation of the actual behaviour of the system.

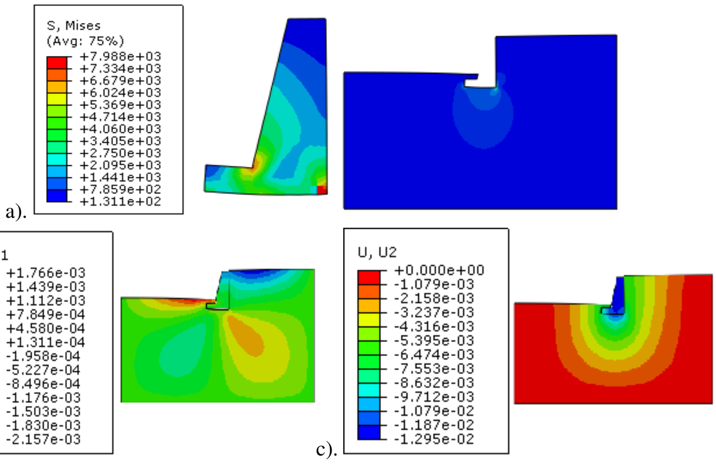

Fig. 13. Gravity retaining wall (Δh=1.5m a) reduced stress in the structure and the surrounding soil, b) horizontal displacement, c) vertical displacement

Fig. 14 presents bar charts of horizontal displacements of the upper edge of the retaining wall (point H) and vertical displacements of the lower ground level (point V) for retaining walls made according to variants 1, 2 and 3. However, Fig. 15 contains the same displacement charts for retaining walls made according to variants 4, 5 and 6.

The horizontal displacement for the selected reference point H (Fig. 14.15) is 13.1 mm for a spread footing reinforced concrete wall, which is the acceptable value. For the wall in Allan Block technology, the displacement is 46.6 mm, while for steel sheet piling it is 52.1 mm. These values may suggest that attention should be paid to the need to monitor the displacement of these structures both during the construction and use.

For variants 4-6, i.e. lower structures, horizontal displacements have smaller values than for variants 1-3. However, also in this case the displacements for the gravity concrete structure are the smallest (2.2 mm), and the displacements for the Allan Block wall (7.3 mm) and the steel sheet pile (8.3 mm) are correspondingly larger. While large displacements of the upper edges of steel sheet piles are understandable (variants 3 and 6) due to their low bending rigidity, the horizontal displacements of the upper edge of the Allan Block wall are surprisingly large (variants 1 and 4).

At point V, vertical soil displacements were studied at the lower level. The use of Allan Block walls caused the largest settlement of soil, which depended significantly on their height Δh and was: 41.1mm for Δh=3.5m, 8.7mm for Δh=1.5m. Soil subsidence for concrete and steel walls was much smaller and also depended on their height Δh. Soil subsidence for concrete walls was equal to 12.6mm for Δh=3.5m and 3.0mm for Δh=1.5m, and soil subsidence for steel walls was 10.6mm for Δh=3.5m and 2.4mm for Δh=1.5m.

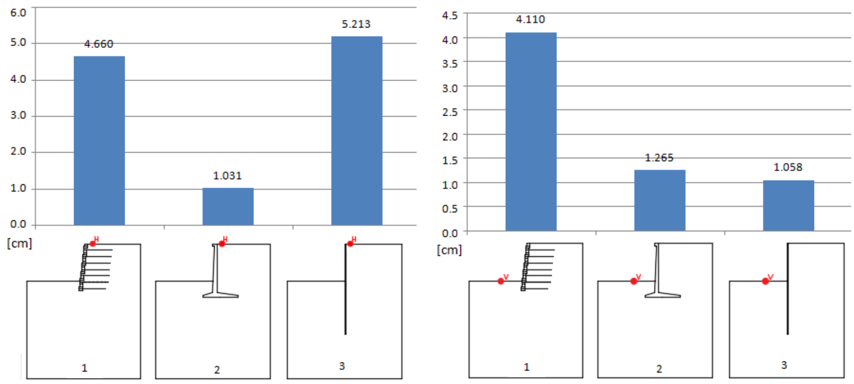

Fig. 14. Variants 1, 2 and 3 (Δh=3.5m): a) horizontal displacements of the H point, b) vertical displacements of the V point

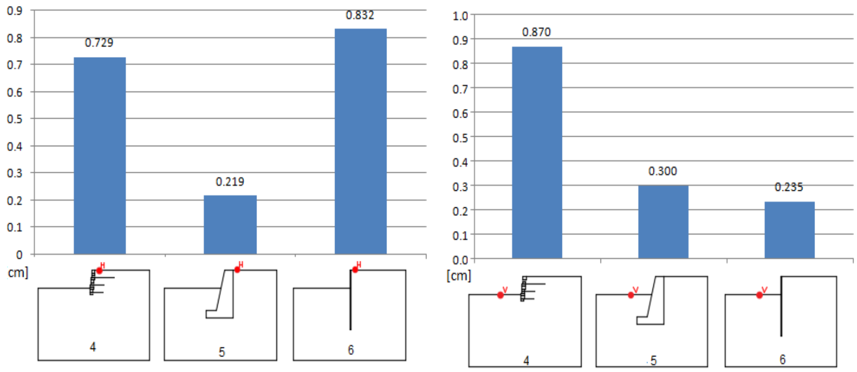

Fig. 15. Variants 4, 5 and 6 (Δh=1.5m): a) horizontal displacements of the H point, b) vertical displacements of the V point

The large vertical displacements found can be related to the fact that the model does not take into account the need for soil compaction after excavation. The use of 3D analysis and consideration of a more complex soil model that is compacted after wall construction would probably improve results. Full analysis could additionally take into account also the method of driving the sheet pile (static or dynamic) and thus affect the realisation of displacement values in variants 3 and 6.

In addition, the conducted numerical analyses allowed checking the stress values in retaining structures and soil. Stresses in individual elements do not exceed the value of material parameters causing their destruction.

4. CONCLUSION

Numerical modelled structures interacting with the soil using the finite element method can be used to analyse various design variants and select the most effective solution in given conditions. Due to the constantly developing technical possibilities, an interesting alternative to theoretical considerations is the quick modeling of various solutions and analysis of the retaining structure and soil behaviour based on calculated displacements and stresses. In addition, the use of modern software can allow for trouble-free change of input parameters, such as the course of the structure in the plan, material characteristics or the type and value of loads. It is certainly a modern approach with extremely interesting development prospects.

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Editor received the manuscript: 07.01.2020