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Research paper

Numerical modelling of gabion retaining wall under loading and unloading

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Abstract: Main goal of this paper is to present results of the numerical simulations of a real-scale gabion retaining wall tests. 4.5 m high wall was loaded and unloaded with water pressure, displacements of the crest of the wall were measured. Finite Element Method was used to simulate experiment and obtained results are compared with experimental ones. Usage of homogenized Coulomb-Mohr type continuum for gabions is proposed. Strength parameters of the model (cohesion and friction angle) are estimated on the base of large scale triaxial tests of the gabions and static tensile tests of the mesh. Influence of the "cut-off" condition on obtained results is analyzed. Elastic model for gabions is used for comparison of the results. Interface elements and truss joints between the gabions are used to simulate joints between gabions with limited strength. Good correlation between displacements obtained in experiment and numerical simulations was observed, especially in loading phase, so presented methodology of numerical modelling allows to model gabion retaining walls behavior close to the reality and could be used in engineering practice.

Keywords: gabion, retaining wall, Finite Element Method (FEM), homogenization, numerical modelling

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1. Introduction

A gabion is a cage, cylinder, or box made of steel wire mesh, filled with rock samples. In civil engineering, gabions are often used to form gravity retaining walls. Despite their simplicity, the numerical modelling of gabion retaining wall-soil interaction is complicated. The main sources of complications are: nonlinear behaviour of the soil (both retained soil and gabion filling), and the interactions (friction) between steel mesh and soil and between gabions. Behaviour of the gabions (on multi-levels, from wire mesh behaviour, through single gabion to full retaining walls construction) is a subject of investigations of many researchers. But so far there are no formal regulations (codes), governing design of such structures (with exception of corrosion protection issues). Usage of ultimate soil pressure theory (identical like for conventional retaining walls) is often advised for stability calculations of the gabion retaining walls.

The entire process of the gabion modeling, which is the scope of this article, is presented in Fig. 1.

Wire mesh static tensile tests and their numerical simulations are described in [1], [3], [4], [5], [8], [12] and [13]. Nonlinear behaviour of the mesh is underlined.

Single gabion cages tests under different loadings are described in [1] and [11]. Results of such tests are used in [4] to calibrate numerical model of the gabion.

Another important issues is modelling of joint between gabions, described in [7]. Friction between gabion and subsoil is analysed in [3].

Numerical modelling of real gabion walls is a subject of [9]. Tests of full-scale gabion walls and their numerical simulations are presented in [1], [[5]] and [10].

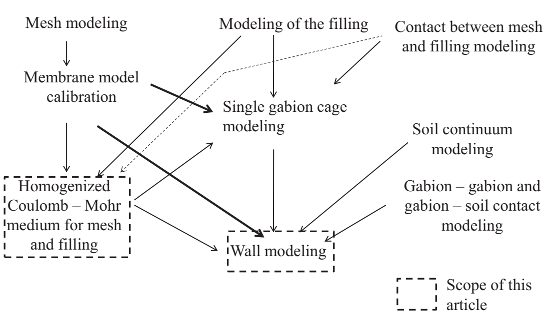


Fig. 1. Scope of this article in the field of gabion modelling

2. Loading – unloading tests of a full scale gabion wall

In this paper results of tests described in [1] were used. 4.5 high gabion wall (see Fig. 2) was built, then subjected to loading and unloading. Horizontal displacements of the crest of the wall were measured. In order to obtain simple loading conditions flexible water tank was used. Controlling of the water level in the tank allowed to load and unload the structure and results in simple loading conditions. During the test significant irreversible (plastic) deformations were observed. It means that elastic model will not properly reproduce displacements of the structure, especially in unloading phase. Displacements in the third direction were blocked, so structure works in the plain strain conditions.

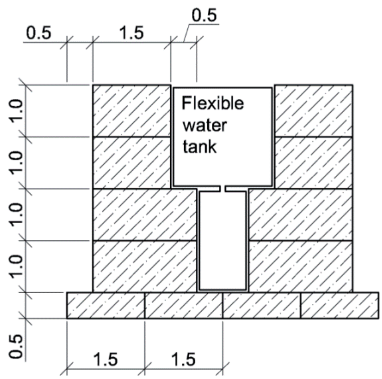


Fig. 2. Gabion wall tested in laboratory (after [1]).

3. Numerical modelling

In order to simulate test described in Chapter 2 numerical modelling was used. All calculations were performed with use of Finite Element Method (FEM) system ZSoil v18. Gabions were modelled as a homogenised Coulomb-Mohr type continuum (mesh + filling). According to [[1]], [[2]] and [[10]] friction angle of a homogenised continuum is equal to the friction angle of the filling and some additional cohesion appears (as an effect of the mesh). Such an additional cohesion could be (according to [[2]] and [[10]]) estimated on the base of large scale triaxial tests from equation:

(3.1)
$$c_r = \frac{\Delta\sigma_3}{2}\tan\left(45^0 + \frac{\varphi}{2}\right)$$

where:

c_r – additional cohesion [kPa], $\Delta\sigma_3$ – increase of the hydrostatic pressure in triaxial test [kPa]

(3.2)
$$\Delta\sigma_3 = \frac{2M\varepsilon_c}{d}\cdot\frac{1}{(1-\varepsilon_a)}$$

where:

ε_a – axial strain of the mesh at failure, according to [[1]] about 0.06-0.07, ε_c – circumferential strain

(3.3)
$$\varepsilon_c = \frac{\left(1-\sqrt{1-\varepsilon_a}\right)}{1-\varepsilon_a}$$

M – elastic moduli of the mesh [kN/m], d – lowest gabion dimension [m]

Elastic moduli of the mesh M could be calculated from equation:

(3.4)
$$M = \frac{f_t}{\varepsilon_a}$$

where:

f_t - mesh tensile strength (kN/m).

Because in the laboratory test displacements in the direction perpendicular to the cross-section plane were blocked, the 2D plain strain model was an obvious choice. Half model (symmetry) was used. According to [1] parameters of the filling were: friction angle of the filling $\phi=32^0$, volumetric weight $\gamma=17.7$ kN/m^3. Taking into account used in the experiment mesh (double twisted 60x80x2 mm) with $f_t=26.5$ kN/m and $\varepsilon_a=0.065$ values of $c_r=27.8$ kPa for $d=1$m and $c_r=55.6$ kPa for $d=0.5$ m were calculated from equations (3.1-3.4). Elastic moduli $E=10$ MPa of the gabions was estimated during back analysis of the loading process, in order to obtain best approximation of the water level –

horizontal displacement of the crest of the wall curve. Value of E could be also estimated on the base of single gabion compression test, which would be a subject of future investigation.

In the numerical simulations performed with use of Coulomb – Mohr model so-called "cut-off" condition (additional plasticity surface, "no tension" condition) is often used. In this paper calculations are performed with and without "cut-off" condition and obtained results are compared. Elastic model is also used, in order to compare obtained results.

Between gabions interface elements were used in order to allow discontinuous displacement field. Friction coefficient in the interface elements was estimated as 90% of the tangent of the internal friction angle of the filling.

In order to simulate joints (made from 2 mm steel wire) between gabions approach described in [7] was used. Two truss elements (connectors) with tensile strength f_t=200 MPa, elastic moduli E=200 GPa and cross-section area A=1cm^2/m each were used in every surface between gabions. This gives typical for gabion structures capacity of the joints F_t=20kN/m. In order to obtain this same strength in the contact surface cohesion in interface elements were estimated as $c = F_t / B$ where B is a contact zone width. This approach leads to values of c=13.3 kPa for 1.5m and c=10 kPa for 2m contact zone width (see Fig. 2 for dimensions of the structure).

Subsoil was modeled as an stiff elastic continuum with E=200 MPa. 4m deep and 6m wide subsoil area was taken into consideration.

Numerical model is presented in Fig. 3. It consists of 1425 nodes, 1122 Q4 continuum elements, 12 truss elements (joints) and 120 interface elements.

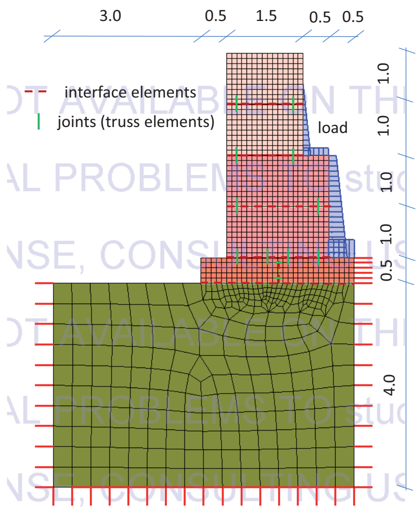


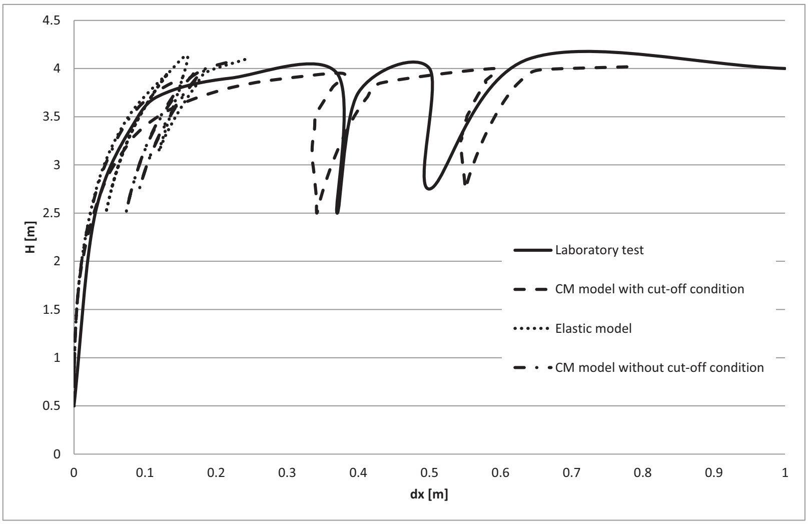
Fig. 3. Numerical model of the wall with boundary conditions.

This same problem was analyzed in [[5]], but only up to the end of first loading – unloading and re-loading was not analyzed. Joints between gabions were also not analyzed and interface elements were not used.

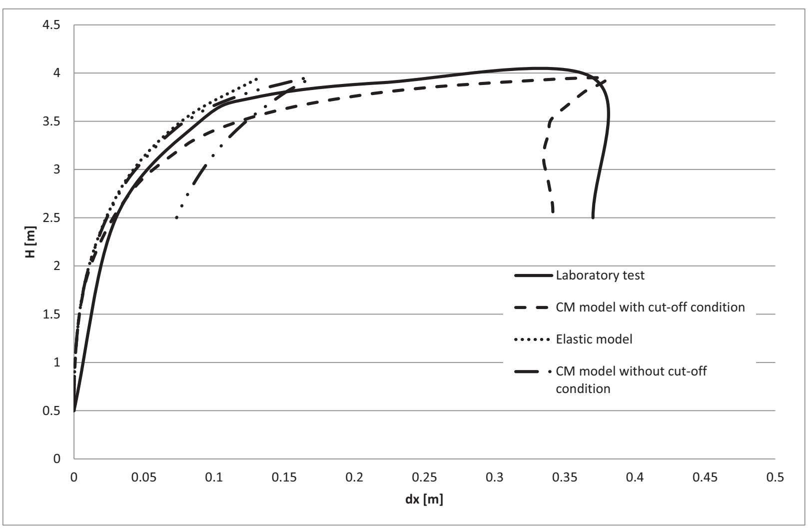
Obtained results show that even simple elastic-perfectly plastic Coulomb – Mohr model with parameters estimated as described above (homogenisation approach) allows to obtain acceptable accordance of the displacements with those obtained in real-scale experiment (see Fig. 4). Accordance is very good in loading path, worse (but still acceptable) in unloading and reloading path. Maximal difference between calculated and obtained in laboratory test horizontal displacement in the first loading phase do not exceed 3 cm (about 9% of the total displacement) and raises to about 5 cm in first unloading phase. In the end of the first reloading phase difference raises to about 7 cm (about 14%), then drops down during second unloading to about 5 cm and becomes almost constant during final reloading.

Irreversible (plastic) part of the deformation is quite visible (as it is pointed in [1]), both in the experiment and numerical calculations. After first loading - unloading process about 90% of the horizontal displacement remains as an irreversible part. Comparison of "water level – displacements" curves obtained with or without "cut-off" condition shows that plastic (irreversible) part of the deformation is mostly governed by such an additional plasticity surface. About 70% of the plastic deformation is an effect of "cut-off condition". Elastic model totally fails in unloading process description.

Vertical displacements (settlements) of the crest of the wall were also analyzed (although they were not measured during the real experiment). Obtained results are illustrated by Fig. 5. Difference between used models are quite visible, but influence of the “cut-off” condition is much smaller than in the case of horizontal displacements. Plastic deformation is also about 90% of the total deformation.

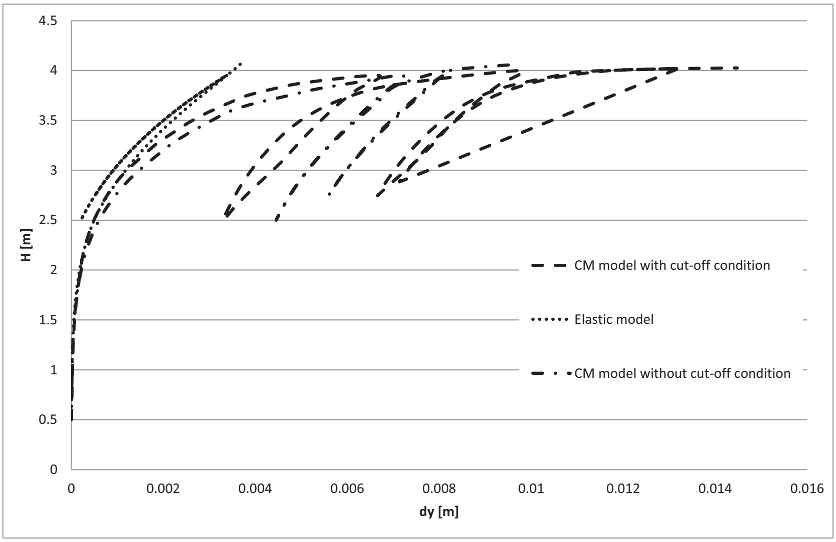


a)

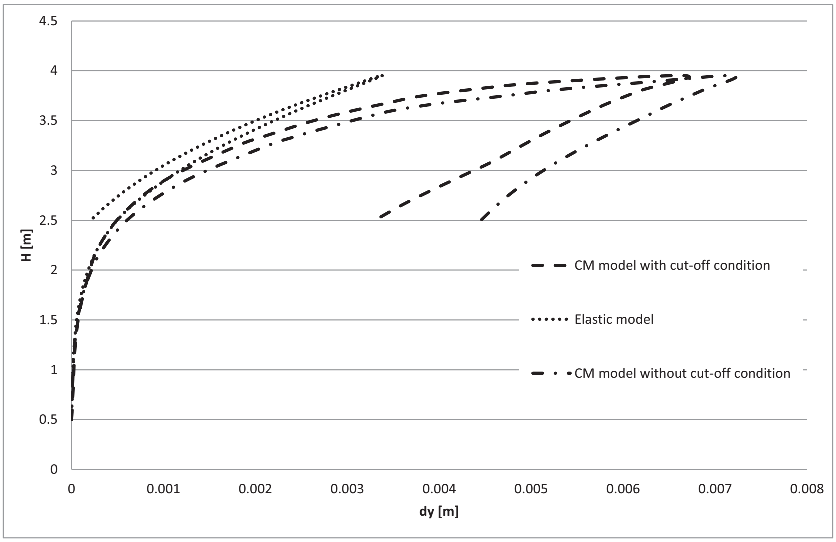


b)

Fig. 4. Water level - horizontal displacement of the crest of the wall curves a) whole test b) up to first unloading



a)



b)

Fig. 5. Water level - vertical displacement of the crest of the wall curves a) whole test b) up to first unloading

4. Final remarks

Presented results of the numerical simulations of 4.5 high gabion wall behaviour under loading and unloading show that it`s possible to reproduce deformation of such a structure with use of Coulomb-Mohr type homogenised continuum for gabions (which is a main novelty of this article). Difference between calculated and measured in laboratory horizontal displacements of the crest of the wall do not exceed 15%. Strong influence of the "cut-off" condition on the obtained results is visible. Elastic model fails in proper description of the unloading process and should not be used in analyses of gabion structures. Described approach could be used in engineering practice, in real gabion structures analysis and design.

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Modelowanie numeryczne muru oporowego z gabionów przy obciążeniu i odciążeniu

Słowa kluczowe: gabion, mur oporowy, Metoda Elementów Skończonych (MES), homogenizacja, modelowanie numeryczne

Streszczenie: Artykuł przedstawia wyniki symulacji numerycznych testów rzeczywistego muru oporowego z gabionów. Mur o wysokości 4.5 m był obciążany ciśnieniem wody i odciążany, mierzono przemieszczenia jego korony. Metoda Elementów Skończonych została wykorzystana do zasymulowania badań laboratoryjnych, porównano uzyskane wyniki z otrzymanymi doświadczalnie. Zaproponowano wykorzystanie zhomogenizowanego ośrodka typu Coulomba – Mohra do modelowania gabionów. Parametry wytrzymałościowe (kohezję i kąt tarcia wewnętrznego) oszacowano na bazie testów trójosiowych gabionów i testów statycznego rozciągania siatki. Analizowano wpływ warunku „cut-off" (braku nośności na rozciągania) na uzyskiwane wyniki. Dla porównania wykorzystano model sprężysty gabionów. Elementy kontaktowe i łączniki kratownicowe wykorzystano do zamodelowania połączeń pomiędzy gabionami o ograniczonej wytrzymałości. Zaobserwowano dobrą zgodność obliczonych numerycznie i pomierzonych laboratoryjnie przemieszczeń (szczególnie w fazie obciążenia), tak więc zaprezentowana metodologia pozwala na bliskie rzeczywistości zamodelowanie zachowania się konstrukcji z gabionów i może być wykorzystywana w praktyce inżynierskiej.

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