Application of joint elements at finite element analysis of embankment dams

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Abstract

An incremental, nonlinear finite element procedure is developed, suitable for deformation, stress and stability analysis of embankment dams with waterproof elements other than earth. The procedure is applied for analysis of hypothetical rock-fill dams with asphaltic facing and an internal asphaltic core - vertical and inclined. Studies are carried out to understand the prototype behaviour of these types of rock-fill dams. Both rock-fill and asphalt behaviour is modelled by using hyperbolic relations. Due to inter-element compatibility, the conventional use of finite element method (FEM) makes impossible the consideration of the effect of differential displacements along the interface of different materials. In order to get a correct and complete analysis in the interfaces rock-fill - rigid foundation, asphaltic facing - concrete cut-off and asphaltic core - transition granular material, joint elements are introduced. In the described studies, a parabolic isoparametric joint element without thickness, numerically integrated, is used. The used model of FEM enables us to get a clear picture of the behaviour of the dam body and the waterproof elements during the incremental construction procedure, as well under the exertion of the water forces. The joint elements enable us to consider the differential displacements along the interface of different materials and contribute to decreasing the number of iterations.

1 Introduction

Embankment dams are ones of the most complex engineering structures. In the last three decades a remarkable progress in their design and construction has taken place. Among the embankment dams, the earth core
Rockfill dams are predominant, due to their reliability, durability and economy. However, under certain conditions, certain kinds of embankment dams with waterproof elements of materials other than earth, appear as a serious alternative. Here, the most important are the reinforced concrete and asphaltic concrete facings, as well the internal asphaltic cores.

The modern period of embankment dams construction has imposed a necessity for the development of suitable methods for the analysis of deformations, stresses and stability of these complex structures. For this purpose, for last three decades the most powerful tool in the hands of the engineers has become the finite element method (FEM), by means of which, numerous homogeneous and zoned embankment dams, real or hypothetical, have been analysed. However, in the literature one can meet just a few examples of embankment dams with waterproof elements made of materials other than earth, analysed by FEM [1,2,3]. The purpose of these papers is to present the influence of joint elements at FEM analysis of hypothetical rockfill dams with different asphaltic waterproof elements in the form of upstream facing, an internal core as well a combination of a vertical core which continue in upstream facing in the upper part.

2 Characteristics of used model of FEM

The displacement procedure of plane strain FEM is applied for the analyses made in this work. The waterproof elements at dams with both asphaltic facing and an internal core, have a very small thickness related to the zones of earth and rockfill materials. In such cases proper values of deformations are of decisive importance for the estimation of the behaviour of the whole structure. This factor has imposed a necessity for the application of a powerful finite element. Therefore a quadratic isoparametric element with eight nodal points has been used, one of the best plane elements. Numerical integration is a fundamental ingredient of isoparametric formulation and this element gives accurate prediction of nonlinear behaviour.

Due to interelement compatibility, the conventional use of FEM makes impossible consideration of the effect of differential displacements along the interface of different materials. Many methods have been proposed to model discontinuous behaviour at the interface of different materials. One of them is to include special joint elements of either zero or finite thickness. The first used joint element, developed by Goodman et al. [4], was destined to represent the interfaces of jointed rock masses. It has found large employment in investigations. Somewhat modified elements for the same purpose have been defined later by other authors, e.g. Ghaboussi et al. [5], Heuze & Barbour [6], and Ge Xiurun [7]. Considerable application the joint elements have found in the analysis of retaining wall behaviour. G. Clough & Duncan [8] used Goodman’s element but in the analysis they involved nonlinear stress-dependent properties of the soil-concrete interface behaviour, approximated by hyperbola. For the same purpose, Nakai [9]
employed a joint element with elasto-plastic properties of soil-structure interface. Day & Potts [10] give a review of many methods proposed to model discontinuous behaviour at the soil-structure interface up to now, analysing the zero thickness element in more detail.

There were just a few examples of application of joint elements in analysis at embankment dams. Sharma et al. [11,12] used isoparametric joint elements at the contacts of the shell and filter and the filter and earth core. The element had zero thickness and six nodal points. The same element was used by Jain at al. [3]. Such kind of parabolic isoparametric joint element, numerically integrated, was applied in the present work. The material behaviour of the joint was considered by using the hyperbolic relations described by Clough W.G. & Duncan [8].

With an eye to the character of the problems studied in this work and the materials involved in the dam body, it was decided that the nonlinear stress-strain behaviour would be expressed by hyperbolic relations, suggested by Kondner and formalized by Duncan and Cheng [13]. The program for analysis is based on an incremental-iterative procedure. The elasticity modulus and Poisson’s ratio are calculated depending on the values of the main normal stresses [14]. The iterative procedure continues till the satisfaction of the condition (1) for all elements:

$$\frac{|E_{ti} - E_{ti-1}|}{E_{ti}} \leq 0.10$$

where $E_{ti}$ and $E_{ti-1}$ are elasticity moduli obtained by two successive iterations.

The numerical analyses were carried out by FORTRAN’s computer code for analysis of problems in mechanics [15], adapted and supplemented for application at embankment dams by authors.

3 Analyses of the results

3.1 Rockfill dam with upstream facing

The cross-section of the first analysed hypothetical dam, 80 m high, is shown on Fig. 1. The parameters of the used materials, given in table 1, are chosen on the basis of our previous investigations [16]. The cross section is discretized with 109 elements, including 17 joint elements, represented by dashed line, Fig. 2. The construction procedure of the dam was simulated in 10 metres thick layers. Then the asphaltic waterproof element was placed in one layer. The water load was taken as a hydrostatic pressure on the dam in three increments.

Before the analysis with joint elements was made, the dam was analysed by using the conventional FEM, without joint elements. Generally, the displacements in the dam body gained by the two manners, differed just slightly. In the contact embankment-rigid foundation, where joint elements are introduced, very small elastic horizontal displacements appear, with values in mm, shown in Fig. 3.
Table 1. Properties employed in analyses of the dam with asphaltic facing

| Parameter | Rockfill | Transition | Asphalt | Interfaces
|-----------|----------|------------|---------|-------------
| $\gamma$ [kN/m²] | 22.50 | 23.00 | 24.00 | Rockfill-foundation | Rockfill-cut-off | Asphalt-cut-off |
| $c$ [kN/m²] | 0 | 0 | 100 |
| $\varphi$ [degrees] | 45 | 45 | 36 |
| $\delta$ [degrees] | | | |
| $c_a$ [kN/m²] | 0.70 | 0.70 | 0.75 | 0.90 | 0.87 | 0.85 |
| $K, K_f$ | 1,500 | 1,700 | 2,300 | 15,000 | 20,000 | 5,000 |
| $K_{ur}$ | 1,850 | 2,100 | 2,800 |
| $n$ | 0.30 | 0.30 | 0.10 | 1.00 | 1.00 | 1.00 |
| $G$ | 0.32 | 0.32 | 0.22 |
| $F$ | 0.13 | 0.13 | 0 |
| $D$ | 9.50 | 9.50 | 0 |

$\gamma$ - unit weight of dam materials; $c$ - cohesion; $\varphi$ - friction angle; $\delta$ - interface friction angle; $c_a$ - adhesion; $R_f, R'_f, K, K_f, K_{ur}, n, G, F, D$ - parameters of the hyperbolic relations.

Figure 1: The cross section of the dam with asphaltic facing

Figure 2: The finite element mesh for the analysed dam

Figure 3: Horizontal displacements at the contact embankment-foundation
However, the joint elements enable a real presentation of the asphaltic layer - concrete cut-off interface behaviour which is in close connection with the possibility to gain a clear picture of state of deformations and stresses in the whole waterproof element. The contours of equal vertical and horizontal displacements for reservoir full conditions at the mentioned interface zone are shown in Fig. 4. In the joint element connecting the asphaltic facing (1 m thick in this lowest part) with concrete cut-off tension occurs. Therefore, the asphaltic facing separates of the concrete cut-off, and it deforms independently. As a consequence, the point 1 moves up for 2.5 mm, and it displaces for 12.7 mm towards downstream. In the same time, the lower point 2 remains immovable. The other points of the lowest, strengthened part of the asphaltic facing, as well in the whole, remained part of the facing, are displaced downwards and downstream. Of course, the interface working in this manner, requires special design in order to remain watertight.

Figure 4: The contours of equal vertical (a) and horizontal (b) displacements at the interface facing - concrete cut-off for reservoir full conditions

The analysis with joint elements gives a real picture not only for deformations, but also for stresses. Fig. 5 shows the diagrams of normal stresses $\sigma_x$ and $\sigma_y$ in the upper edge of the waterproof element. The conventional analysis, as a consequence of joint compatibility, gave tensile stress for $\sigma_x$ equal to 500 kN/m$^2$ at the lowest point (1, Fig. 4). Just the opposite occurs in the analysis with joint elements, which, what is to be expected, gives at this

Figure 5: Normal stresses at the facing
point compression, Fig. 5. Tension appears only at the upper end of the facings, near the dam crest, but with a value smaller than 20 kN/m².

Another benefit of the joint elements introduced in the above described analysis was the saving of time. Namely, the number of iterations for each incremental load was decreased from 5-7 at the analysis without joint elements, to 3-5 at the analysis with joint elements.

3.2 Rock-fill dam with internal asphaltic core

In the case of a rock-fill dam with an internal asphaltic core, also 80 m high, the joint elements were introduced at the interfaces asphaltic core - transition material, Fig. 6.

The contours of equal vertical (a) and horizontal (b) displacements in the dam body are presented in Fig. 7. At the embankment material-asphaltic core interfaces, the discontinuous behaviour is evident. In consequence of this opportunity, the load transfer is more real, occurred between adjacent different a core and transition's materials.

Figure 7: The contours of equal vertical (a) and horizontal (b) displacements
3.3 Combined solution

Fig. 8 shows the discretization of a rockfill dam with a combination of a vertical asphaltic core which continues in upstream facing in the upper part, planned to be constructed in three stages. In this case it is necessary to apply joint elements at the interface between identical rockfill materials, but placed in different stages (stage 2 and 3, Fig. 8). Without this measure, the interelement compatibility causes tension in the elements of stage 3, adjacent to the elements of stage 2.

![Figure 8: Discretization of the dam with combined waterproof element planned to be built in three stages](image)

4. Conclusions

The Finite element method is a powerful tool for analysis embankment dams. However, correct and complete analysis of embankment dams with asphaltic waterproof elements requires obvious application of joint elements at the contacts of different materials. Zero thickness parabolic isoparametric joint element with six nodal points enables us to consider the differential displacements along the interface of different materials and contributes to a decreasing the number of iterations.

When the dam is to be built in more stages, to gain a real simulation of the dam behaviour, joint elements should be applied even at the interface of identical embankment materials. Without this measure, the interelement compatibility causes tension in the elements of the newer stage.

References


16. Tančev, L. Static analysis of embankment dams, Studentski Zbor, Skopje, 1989 (in Macedonian)