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Workability of high rockfill dam with a polymer face

Работоспособность высокой каменно-набросной плотины с полимерным экраном

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Key words: geomembrane; rockfill dam; combined dam; stress-strain-state; numerical modeling; strength; soil-cement; Bovilla dam; perimeter joint

Ключевые слова: геомембрана; каменно-набросная плотина; комбинированная плотина; напряжённо-деформированное состояние; численное моделирование; прочность; грунтоцемент; плотина Бовилла; периметральный шов

Abstract. The results of numerical study of stress-strain-state (SSS) of a rockfill dam with a face whose main watertight element is a polymer geomembrane. Analyses were conducted with consideration of non-linearity of contact interaction of structure elements and non-linearity of soil behavior. Bar finite elements were used for modelling of the thin geomembrane. The study was conducted on the example of Bovilla dam structural design which was built in 1996 in Albania. Initially Bovilla dam was planned to have a reinforced-concrete face, but later there was realized the design with multy-layered face consisting of PVC geomembrane, the underlying layer of soil-cement and a protection layer of reinforced concrete slabs. The face is conjugated with the concrete structure being an integral part of the dam. The results of numerical analyses showed that the weakest part of the dam design is the place of conjugation of the face with the concrete structure. The joint between the face and the concrete structure opens and the face shifts with relative to concrete surface. The polymer geomembrane may withstand these displacements without damages because the face structural design is provided with a compensating device in the form of a geomembrane loop. However, as calculations showed, the face design provokes formation of tensile stresses in protection reinforced concrete slabs and in the soil-cement underlying layer. In case the dam face was made of reinforced concrete, cracking in the face could be less probable. In our opinion, more feasible solution of the conjugation zone could be the alternative when the polymer geomembrane is placed over the face and is covered by soil protection layer. Taking into account high strength and safety of polymer geomembranes they may be recommended to be used as a backup seepage-control element of high concrete faced rockfill dams.

Аннотация. Рассматриваются результаты численного исследования напряжённо-деформированного состояния (НДС) каменно-набросной плотины с экраном, основным водонепроницаемым элементом которого является полимерная геомембрана. Расчёты проводились с учётом нелинейности контактного взаимодействия элементов конструкции и нелинейности поведения грунтов. Моделирование тонкой геомембраны использовались стержневые конечные элементы. Исследование проведено на примере конструкции плотины Bovilla, построенной в 1996 году в Албании. Первоначально плотину Bovilla планировалось выполнить с железобетонным экраном, но в последствии была реализована конструкция с многослойным экраном, состоящим из PVC-геомембраны, подстилающего слоя из грунтоцемента и защитного слоя из железобетонных плит. Экран сопрягается с бетонным сооружением, являющимся составной частью плотины. Результаты численных расчётов показали, что наиболее уязвимым узлом конструкции плотины является узел сопряжения экрана с бетонным сооружением. Шов между экраном и бетонным сооружением раскрывается, а экран смещается относительно поверхности бетона. Полимерная геомембрана может выдержать данные перемещения без повреждения, т.к. конструкция экрана предусматривает устройство компенсатора в виде петли геомембраны. Однако, как показали расчёты, конструкция экрана с компенсатором такова, что провоцирует образование растягивающих напряжений в защитных железобетонных плитах и подстилающем слое из грунтоцемента. В случае, если бы экран плотины был выполнен железобетонным, трещинообразование в экране была бы менее

вероятным. По нашему мнению, более удачным решением узла сопряжения был бы вариант, когда полимерная геомембрана уложена поверх экрана и закрыта защитным слоем грунта. Учитывая высокую прочность и надёжность полимерных геомембран, можно рекомендовать использовать их к дублирующий противофильтрационный элемент высоких каменно-набросных плотин с железобетонными экранами.

Introduction

At present the sphere of using synthetic (polymer) materials in hydraulic engineering is expanding. One of the promising trends of this process is use of polymer geomembranes as seepage-control elements in dams and dikes [1–5]. Already 60 years ago the polymer films started to be used for combating seepage in dams and dikes, but mainly in temporary structures [2, 6–8]. By present the possibilities of using polymer items have considerably increased; they became safer. Due to large thickness the modern geomembranes have good puncture resistance. During laboratory tests [9, 10] and field tests [11] it was established that polymer geomembranes may be used for a very long time. The guaranteed life of open geomembranes is 50-100 years [10]. Operation conditions of closed geomembranes in the dams working at temperatures about 0°C are the most favorable for polymer materials, therefore, many of them (for example, high-density polyethylene) may be effective for several hundred years [9].

Experience in hydraulic engineering shows, that up-to-date geomembranes may serve as seepage-control elements (SCE) of high dams. Namely, covered by a membrane the upstream face of concrete dams and reinforced concrete faces of rockfill dams may be repaired [2, 12, 13]. A number of dams have been constructed where SCE was arranged of geomembrane [2, 14].

In this regard, the type of an embankment dam appears to be promising, in which the main SCE is a polymer geomembrane, laid on smooth rigid bedding. This bedding may be arranged both of concrete and of a cheaper material - soil cement, i.e. mixture of soil with cement

Such a construction was realized in Bovilla dam in Albania in 1996 [1, 2, 15, 16]. This is the highest dam in the world with a seepage-control element made of a polymer geomembrane. The height of the earthfill dam is more than 71.6 m. Bovilla dam has a combined structure – a concrete water-retaining structure with a height of approximately 25 m is integrated in the combined dam (Fig. 1). It is deepened into a rock foundation. Taking into account the embedment of the concrete structure into the foundation the maximum construction height of Bovilla dam is almost 81.6 m. The rockfill is arranged with a lower slope of 1.6. The slope of its upstream face is variable - in the upper part it is 1.55, in the lower part it is 1.6. [1, 2, 15, 16].

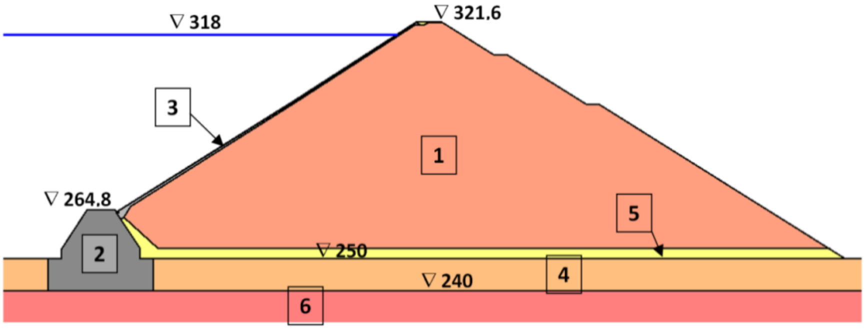


Figure 1. Cross section of Bovilla dam
1 – rockfill shell, 2 – concrete structure, 3 – multi-layer face, 4 – foundation soil layer,
5 – filter layer, 6 – rock foundation

Initially Bovilla dam was designed with reinforced concrete face, but then it was decided to change its structural design. The dam has a face of 3 mm thick PVC geomembrane. The face is placed on the layer of soil-cement bedding about half meter thick. From the upstream side the polymer face is covered with 20-30 cm thick precast concrete slabs. From both sides the geomembrane is protected by a geotextile layers. Thus, the seepage-control element has a complicated multi-layer structure where the geomembrane is the main but not the only one seepage-control measure.

The most complicated part in Bovilla dam design is conjugation of the rockfill part seepage-control face with concrete structure. The geomembrane is rigidly attached to concrete, but is placed with formation of a loop (compensator) permitting the face extension and displacement [2, 15]. A sand pad is provided between the soil-cement concrete and the reinforced concrete face to provide geomembrane free displacements.

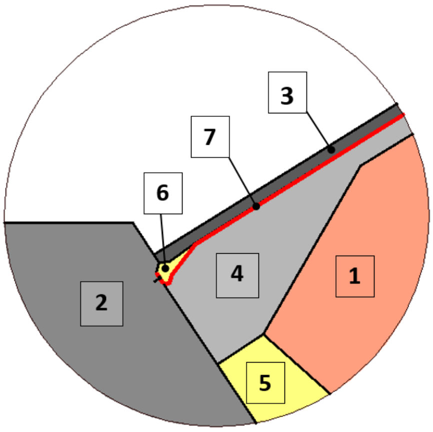


Figure 2. Design of contact zone between the face and the concrete structure.
1 – rip rap, 2 – concrete structure, 3 – reinforced concrete slabs, 4 – soil-cement bedding,
5 – filter layer, 6 – sand pad, 7 – geomembrane.

We studied stress-strain-state (SSS) of Bovilla dam design to assess safety of its SCE, including the place of its conjugation with the concrete structure. Besides, the task was assigned for assessment of effectiveness of the design solution for use of a polymer face in comparison with other structural alternatives.

For this purpose SSS of three SCE alternatives of rockfill dam were studied:

Alternative 1 – continuous by length reinforced concrete face (RCF) laid on soil-cement bedding. This is the initial non-realized alternative of Bovilla dam SCE;

Alternative 2 – realized SCE design where the polymer face was laid on soil-cement bedding and on the top covered with reinforced concrete slabs ;

Alternative 3 – SCE differing from that realized at Bovilla dam (alternative 2) by the fact that the polymer face was laid not on soil-cement bedding but on soil (sand-gravel) bedding.

Methods

SSS studies were conducted by finite element method with the aid of software worked out by Dr. Ph. (Tech) M.P. Sainov [17]. There were considered conditional flat cross section of the dam.

The finite-element model of the structure for Alternative 1 consisted of 730 finite elements, for Alternatives 2 and 3 – 830 finite elements. In calculations the non-linear character of interaction between non-soil structural elements and soils was taken into account. For this purpose the contact finite elements were introduced. In the model of Alternative 1 there were 83 such elements and in Alternatives 2, 3 – 128. The geomembrane in Alternatives 2, 3 was modelled by 27 bar finite elements.

In order to provide, at great difference between rigidity values of structural elements composing the dam, the sufficient accuracy of the obtained results of analyses all the finite elements had cubic approximation of displacements. The total number of degrees of freedom in the Alternative 1 model was 6854, in Alternatives 2, 3 – 7372.

During analyses the staged dam construction was taken into account: 32 design steps each simulating either construction of part of the structure or the reservoir filling.

For modeling non-linear behavior of soil medium the model of Professor L.N. Rasskazov was used [18]. Deformation properties of rockfill were assumed by analogs. The rockfill averaged modulus of deformation amounted to about 60 MPa.

Non-soil materials were assumed to be linearly deformed. For reinforced concrete the modulus of deformation was taken equal to 29000 MPa, Poisson's ratio – 0.18. For soil-cement the modulus of deformation was taken equal to 5000 MPa, Poisson's ratio 0.22. For geomembrane material the modulus of deformation was taken equal to 1000 MPa, which approximately corresponds to that of HD polyethylene (high density) [1]. In contacts there was used a non-linear model permitted their opening and slip.

Results and Discussion

By the results of analyses at the adopted properties of rockfill the maximum settlement of an embankment dam under its own weight amounts to 33 cm. The face under hydrostatic pressure displaces for 16.2 cm in direction normal to the slope surface (Fig.3).

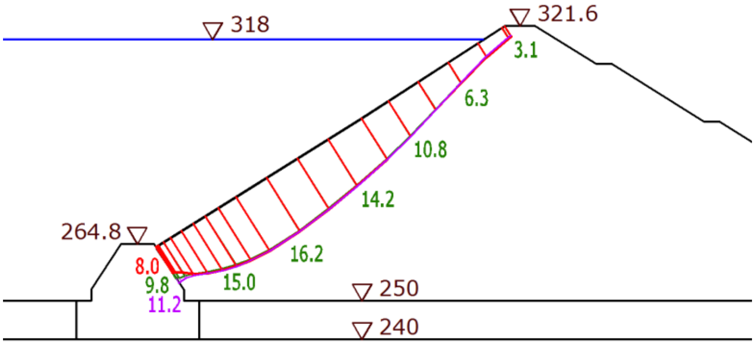
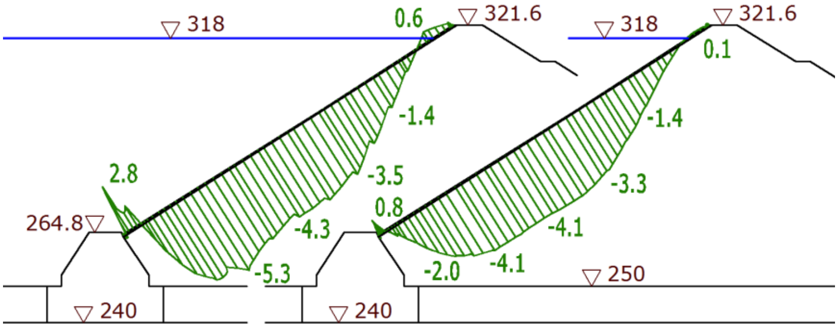


Figure 3. Displacements of the dam upstream face in perpendicular direction (deflections, cm). The green color indicates displacements for Alternative 2, red – for Alternative 1, violet – for Alternative 3.

In the zone of the face conjugation with the concrete structure the displacements of the upstream face are not equal to 0, because soil of the embankment dam slips relative to the concrete surface. The face displacement relative to the concrete structure comprised 8÷12 cm depending on the Alternative (Fig. 3). Besides, there observed opening of the joint between reinforced concrete slabs covering the upstream face and the concrete structure. In Alternative 1 it amounted to 1.8 cm, in Alternative 2 it was 2 cm.

The zone of conjugation between the earthfill and concrete structures is the weakest and the least safe zone in the dam design. In this zone the soil mass (and contact “concrete-earth”) is subject to complicated deformations and has unfavorable SSS. This also affects the SSS of reinforced concrete face (Alternative 1), reinforced concrete layer (Alternatives 2, 3), covering the dam upstream face.

In Alternative 1 the lower part of RCF adjoining the concrete structure is subject to deflection toward the upstream side, while the rest part deflects toward the downstream side. As a result tensile stresses in direction along the face (longitudinal stresses) arise in the RFC lower part. On the upper face of RCF they reach 2.8 MPa (Fig.4a). These stresses exceed design tensile strength of concrete. The rest part of RCF is compressed in longitudinal direction by stresses with values up to 5.3 MPa.

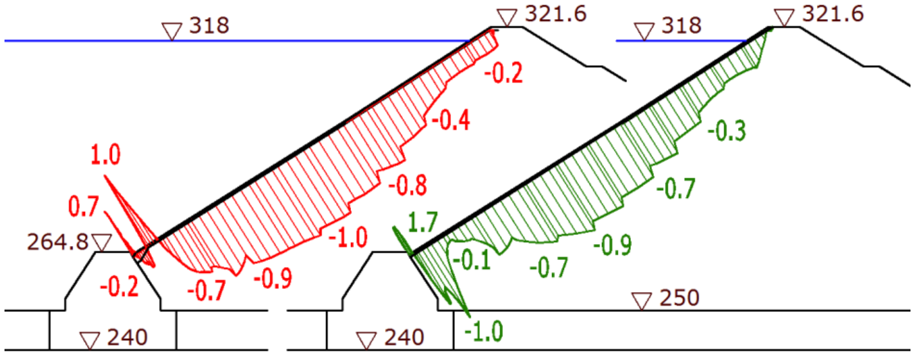


a) **b)**

Figure 4. Longitudinal stresses in reinforced concrete face (MPa) in Alternative 1 a – on the upstream face, b – on the downstream face

Soil-cement under-face zone also has unfavorable SSS in the zone of contact with the concrete structure. Tensile stresses in it in longitudinal direction reach 1.7 MPa (Fig. 5b).

Thus, we may expect formation in RCF and in the under-face zone of transversal cracks which threaten water tightness of the dam SCE. This explains the reason why at designing Bovilla dam it was decided to refuse from RCF and choose the polymer face.



a) b)

Figure 5. Longitudinal stresses in the soil-cement bedding downstream face (MPa)
a – Alternative 2, b – Alternative 1.

However, at transfer to multi-layer structural design of SCE (Alterantive 2) the strength condition of the embankment dam constructions in the zone of contact with the concrete structure did not improve. This is connected with complicated arrangement of the interface zone. In the already constructed dam to provide geomembrane free deformations a cavity was provided between the concrete slabs and their soil-cement bedding. The soil-cement zone was expanded to avoid weakening of soil-cement bedding due to arrangement of the cavity.

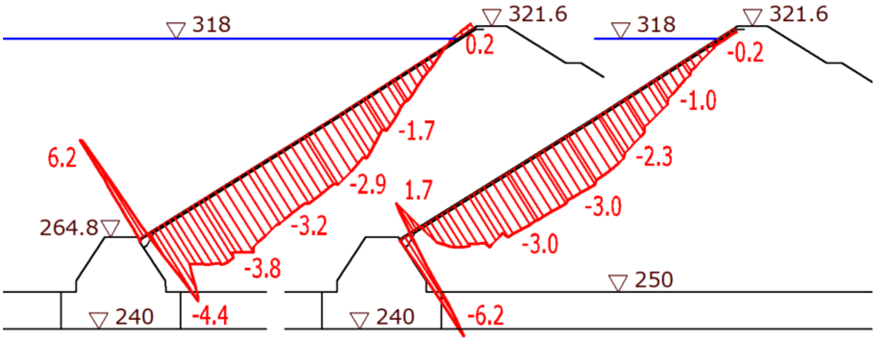
Such design of the interface affects its operation. Analyses permitted revealing the following pattern of this interface operation. Under the action of hydrostatic pressure the face tends to «slip» and turn relatively the concrete structure. But at turn the lower end of the soil-cement zone rests on the concrete structure, which cause in it concentration of compressive stresses of about 3 MPa. Due to presence of the thrust practically on the entire length, the contact of the multi-layer face and the concrete structure opens. The largest opening (2 cm) is observed on the top of the dam face.

In addition, the presence of a cavity between the concrete coating and soil-cement bedding affects the interface SSS (Fig. 2). Concrete cover with one part is pressed into the cavity, while the other is supported by low-compressible bedding. Due to this, the concrete cover undergoes strong bending deformations.

Due to bending, the top face of the coating of reinforced concrete slabs experiences tensile longitudinal stresses, which reach 6.2 MPa (Fig. 6b). The zone of tension extends to 5.8 m. A zone of tensile stresses is also formed on the downstream face at a certain distance (Fig. 6b). Thus, the formation of cracks in the reinforced concrete coating is inevitable.

The unfavorable SSS also has an under-face zone of soil-cement (Fig. 5a), and cracking is also expected in it.

Thus, water impermeability of SCE is entirely determined by the integrity of the polymer geomembrane.



a) b)

Fig.6. Longitudinal stresses in the reinforced concrete cover (MPa) in Alternative 2
a – on the upstream face, b – on the downstream face.

By the results of analyses due to the openings and shear movements on the contact of the face with the concrete structure, the geomembrane undergoes deformations of the elongation. The geomembrane's loop thus straightens. Due to straightening the deformations of elongation do not cause significant tensile stresses in the geomembrane. According to the results of analyses with deformation modulus of 1000 MPa, the maximum of tensile stresses is only 0.5 MPa. This is much less than the tensile strength of polyethylene (30 MPa). If we assume that the geomembrane is made of PVC, then the safety margin of the geomembrane will be even higher.

In the rest of the geomembrane parts no significant stresses occur.

Thus, the design of the interface of a multi-layer screen with a concrete structure ensures integrity and reliability of geomembranes at displacements on the contact between two structures, but at the same time provokes crack formation in the elements protecting the geomembrane: in the cover of reinforced concrete slabs and in soil-cement bedding. Damage to these rigid structures is dangerous for the geomembrane, because sharp edges of damaged elements may cause a puncture.

Therefore, another calculation was carried out - for Alternative 3, in which the hard soil-cement bedding was replaced with gravel-sand. The analyses showed that in this case the state of the interface is somewhat improved, but not radically. Opening of the joint decreases to 1.7 cm, but the face displacement relative to the concrete structure increases to 11.2 cm (Fig. 3). Also, as in Alternative 2, a zone of tensile longitudinal stresses is formed on the upstream face of the reinforced concrete cover. However, they do not exceed 4.7 MPa (Fig. 7a).

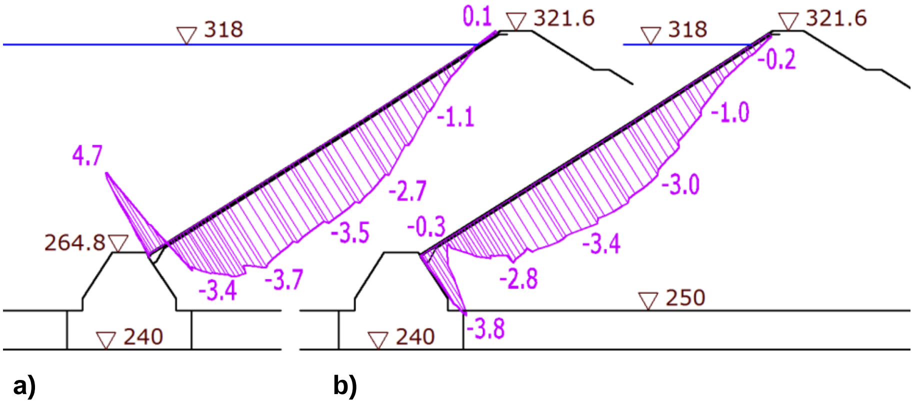


Fig.7. Longitudinal stresses in the reinforced concrete cover (MPa) in Alternative 3
a – on the upstream face, b – on the downstream face.

Thus, in Alternative 3 damages of reinforced concrete cover and subsequent puncture of geomembrane may occur. In order to avoid them it is better to refuse from using concrete cover in the lower part of the dam and substitute it by a layer of impervious soil. Similar design of interface was used during repairs of New Exchequer dam [19]. New Exchequer dam is of similar design as Bovilla dam; it also refers to combined dams, but is was made not with a polymer face but with a reinforced concrete face. In this dam the conjugation place of the reinforced concrete face and the concrete structure is covered on the top by a geo-membrane, which in its turn is covered by a soil layer.

This example shows that at construction of Bovilla dam it was not necessary to refuse from the reinforced concrete face in favor of the polymer face. It was sufficient to lay a geo-membrane in the lower part of the face to provide water tightness. It should be stressed that substitution of the reinforced concrete face by a polymer face did not decrease the cost of Bovilla dam, because its structural design envisages maintaining the reinforced concrete cover of the upstream slope for protection of the polymer face.

The advantage of using the polymer face is a high level of safety of the dam seepage control facility. The example of Boviila dam permits recommending for construction of ultra-high dams the use of combined (double) seepage-control element consisting of reinforced concrete (or soil-cement) face covered by a geo-membrane. However, the geo-membrane should not be open, because otherwise its service life decreases. It is reasonable to cover the combined seepage-control element with a soil layer. Earlier we recommended the dam of such structural design [20].

Conclusions

Use of polymer geomembrane as a seepage-control face of a high rockfill dam significantly improves the reliability of the dam seepage-control facility. This is because polymer materials have high strength and elasticity, which allows them to experience significant deformations inherent in embankment dams without damage. Rockfill dams with a seepage-control face of polymer geomembrane are more efficient type of dams than dams with reinforced concrete face. Rational solution is the construction of rockfill dams with a combined (double) seepage-control element, including a reinforced concrete (or soil-cement) face covered with a geomembrane/

The most vulnerable node of a dam design with a polymer face is its interface with a rock foundation or a concrete structure. In this zone, one can expect the appearance of tensile stresses in the geomembrane. Used in the Bovilla dam conjugation (which provides arrangement of the geomembrane loop) ensures the integrity of the geomembrane, even with significant movements at the interface. However, there is a risk of damage to the protective layers of the geomembrane, which may entail damage to the geomembrane. Apparently, it is more rational to provide a protective coating in the compensator assembly of the geomembrane not of rigid concrete slabs, but of soil or other pliable material, as was done during repairs of New Exchequer dam.

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