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Pregledni naučni članak

НЕКИ АСПЕКТИ ФИЗИЧКОГ И АНАЛИТИЧКОГ МОДЕЛИРАЊА КОНТАКТНЕ СМИЧУЋЕ ЧВРСТОЋЕ У ГЕОТЕХНИЦИ

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РЕЗИМЕ

У раду су приказани значајнији аспекти моделирања контактне смичуће чврстоће дуж површина различитог карактера. Посебно су анализирани физички и аналитички аспекти моделирања, преко приказа резултата испитивања методама развијених на Катедри за геотехнику на Грађевинском факултету у Скопљу, Р. Македонија. Методе су осмишљене у фазама геотехничких истраживања за насуту брану “Козјак” и лучну брану “Света Петка” на реци Трески у близини Скопља. Аутори сматрају да искуства могу бити од значаја за будући развој нових или модифицирања неких од познатих метода, јер је ово један од кључних проблема у геотехници.

КЉУЧНЕ РЕЧИ: Геотехника, контакти, моделирање, смичућа чврстоћа

SOME ASPECTS OF PHYSICAL AND ANALYTICAL MODELING OF INTERFACE SHEAR STRENGTH IN GEOTECHNICS

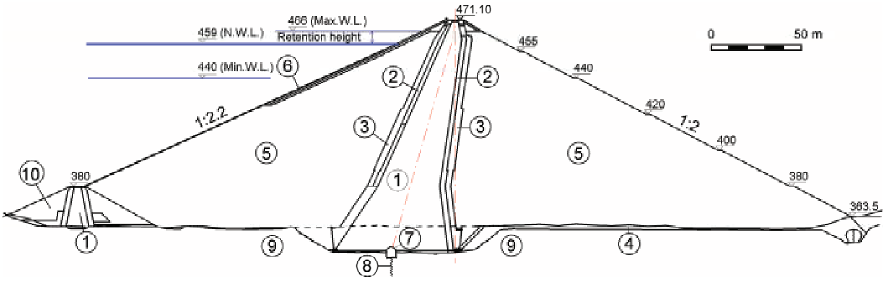
ABSTRACT

Some important aspects in modeling of shear strength along different interfaces are presented in the paper. A special attention is given on physical and analytical aspects, through presentation of results obtained from testing methods developed at the Chair of Geotechnics at the Faculty of Civil Engineering in Skopje, R. Macedonia. The methods are developed in different phases of geotechnical investigations for earth fill dam “Kozjak” and arch dam “Sveta Petka” at river Treska near Skopje. Authors believe that presented experiences can be important for future development or modifications of some known methods, because this is one of the key questions in geotechnics.

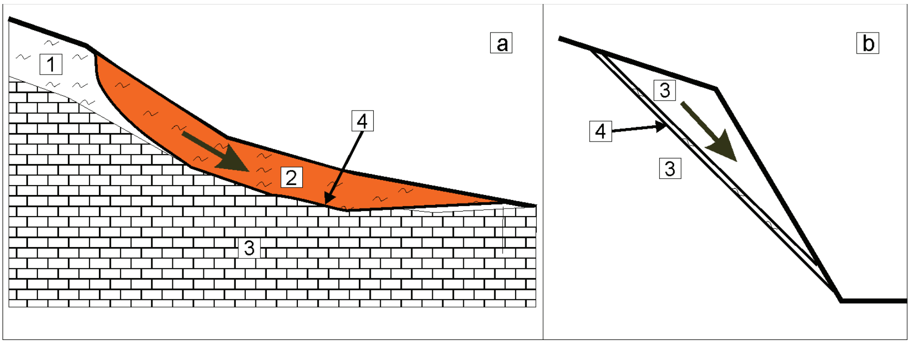
KEY WORDS: Geotechnics, interfaces, modeling, shear strength

INTRODUCTION

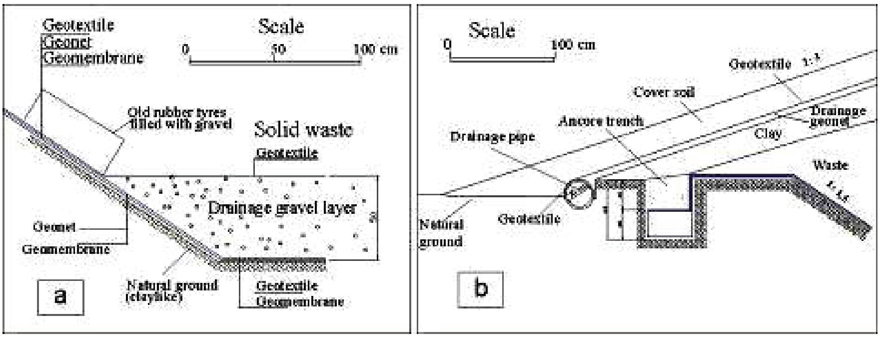
Rational, safe and efficient designing in geotechnics is not possible without knowing in detail physical and mechanical properties of the natural media from one, and the elements of artificial structures, at the other side. In fact, one of the key questions in geotechnics is investigation, physical, analytical and numerical modeling of the interface shear strength as very important parameter in interaction analyses. This aspect is present in almost all geotechnical problems. Some examples are presented in Figure 1 to Figure 3.



Слика 1 Карактеристични попречни пресек насуте бране Козјак на реци Трески, Р. Македонија, као пример различитих контактних површина: (1) глинено језгро; (2) прва и (3) друга филтрациона зона; (4) речни нанос; (5) камени набачај; (6) ређани камен; (7) инјекциона галерија; (8) филтрациона завеса; (9) крута чврста основна стенска маса; (10) шљунак
Figure 1 Main cross section of earth fill Kozjak Dam at river Treska, R Macedonia, as an example for several types of interfaces: (1) Clay core; (2) first, and (3) second transition zone (filter); (4) river deposit; (5) rock fill shells; (6) arranged stones; (7) grouting gallery; (8) grout curtain; (9) rigid hard rock mass foundation-marble; (10) gravel



Слика 2 Нестабилности косина дуж контактних површина: а) клизање тла дуж контакта са чврстом стеном у основи; б) клизање дуж контакта стена-глиновита испуна-стена
Figure 2 Slope instabilities along interfaces: a) sliding of soil along interface between soil debris and hard rock mass in the bedrock; b) Sliding along contact rock mass-clay infilling-rock mass



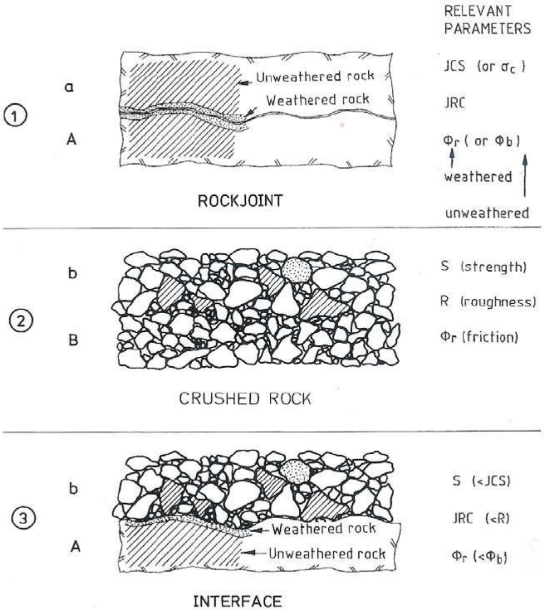
Слика 3 Приказ контактних површина код депоније: а) основа депонијског тела са елементима дренаже и обложног система; б) детаљ покривног система
Figure 3 Presentation of interfaces at waste disposal: a) the bottom of the landfill body with elements of drainage and single liner system; b) detail of the covering protective layer

It is clear that interfaces can be connected with zones at rock foundation and all installed materials in rock fill, earth fill or concrete dams, landslide shear zones, rock mass joints with clay or other infilling, geosynthetics reinforcements in slopes, solid waste landfills, interfaces concrete-concrete, concrete-rock mass foundations, concrete-grouting mixture-concrete at radial joints of arch dams, rock to rock contacts, etc. From this, the importance of development of methods to define interface shear strength is more than obvious.

PRESENTATION OF SOME IMPORTANT PREVIOUS RESEARCHES

On the current level of development in geotechnics, several approaches of shear strength testing are known, but there are still cases when it is very usual to assume them, and very often this problem is not even treated. Along with this, it is very difficult to conclude how close is the prognosis of the parameters to the actual conditions which are expected in the phase of exploitation of the structures. It can be mentioned that many laboratory experimental testing methods are developed in soil and rock mechanics, especially when behavior of homogenous soils is of interest. Methodologies for testing shear strength along discontinuities are also developed (Goodman 1974; Barton and Bandis 1974, etc). Furthermore, there are some developed methodologies to define shear strength along interfaces concrete-rock mass in a phases of design for concrete dams (Kujundžić, 1978; Čolić, 1983; Anđelković, 1998; Jovanovski et al., 2002; and others). Some detail analyses of shear strength parameters in designing of earthfill dams can be found in Barton and Kjaernsli (1981), while summarized overview is given by Tančev (1989).

On the other hand, shearing strength parameters along interface of different materials which are composed during construction of rockfill dams, are treated very rarely in the scientific literature, even though certain data for these problems can be met (Jovanovski et al., 2004; Barton, 2008; Papić et al., 2011). Just to illustrate the interfaces problem, some schematic illustration for relevant controlling parameters is shown in Figure 4 (Barton, 2008).



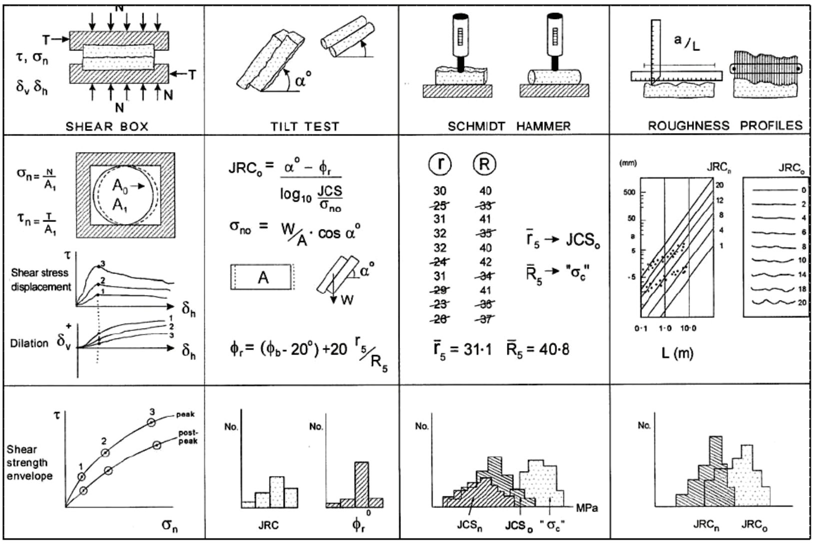
Слика 4 Контакт: 1) напрегнутих пукотина у стенама; 2) између зрна унутар каменог набачаја; 3) каменог набачаја и стенске основе

Figure 4 Contact across: 1) stressed rock joints; 2) rockfill inter-particle; 3) rockfill lying on a rock foundation: JRC-Joint Roughness Coefficient, JCS-Joint Strength Coefficient (Barton, 2008)

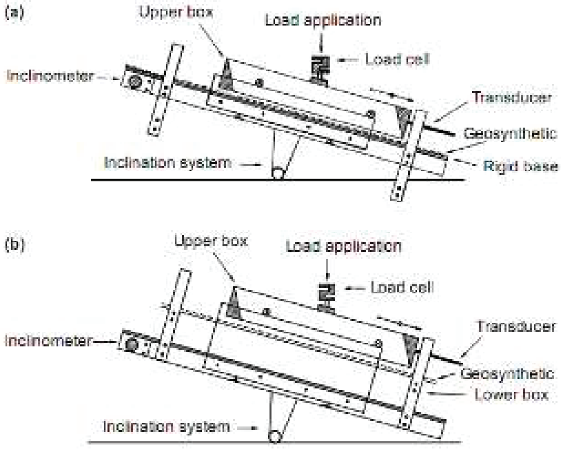
A range of index tests has been developed for estimating shear strength of rock joints, so that a statistical range of roughness and strength values can be accommodated in design, without need for an equally large number of direct shear box tests, as illustrated in Figure 5.

An adequate attention is given on the estimation of interface shear strength for geosynthetic systems, like shear behaviour of geosynthetics in inclined plane test and influence of soil particle size presented by Lopes et al (2001). The used equipement is presented in Figure 6. Methods for interpretation of laboratory generated interface shear strentgh for geosysnthetics is given by Koerner and Koerner (2011). Results from large scale direct shear strentgh for geomembranes is presented by Jose et al. (2008).

An interesting physical concept for estimation of safety factor in landslides and in rock-block stability analyses can be application of shear strength envelope illustrated by Spasojević and Šušić (1995) for soil-like sliding, and by Jovanovski and Gapkovski for hard rock masses (2004).



Слика 5 Приказ неколико метода за дефинисање смичуће чврстоће дуж пукотина у стени и контаката у каменом набачају
Figure 5 Illustration of several methods to define shear strength along rock joints and rockfill inter-particle contact (Barton, 2008)

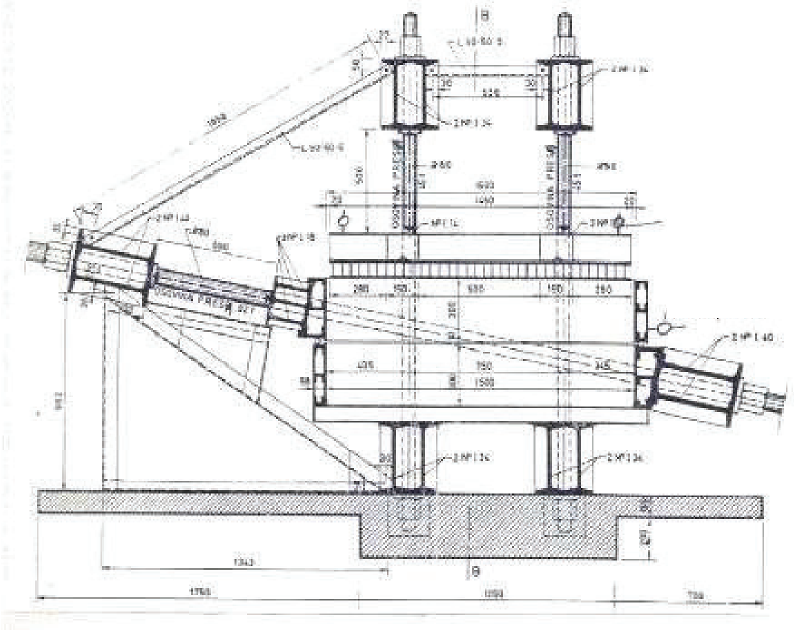


Слика 6 Шематски приказ апарата са закошеном равни: а) крута основа и горња кутија; б) доња и горња кутија
Figure 6 Schematic representation of the inclined plane apparatus: a) rigid base and upper box; b) lower and upper boxes (Lopes et al., 2001)

But, although a number of methods are available, it is obvious that no particular method can be universally accepted for several reasons. For example, there are wide range of variations in shear strength values of rock mass, concrete, clay infilling, rockfill, etc., while a lot of difficulties are connected with testing equipment limitations, scale effect etc. A real approach is for each engineering problem to apply adequate methodology of testing, so some of the methods presented further in the text, can be useful in practice and can help in scientific development in geotechnics.

ONE METHODOLOGY FOR PHYSICAL MODELING OF INTERFACE SHEAR STRENGTH AT EARTHFILL DAMS

The idea for defining contact properties for a case of construction of earth fill dam came out in the Chair of Geotechnics at the Faculty of Civil Engineering in Skopje, R. Macedonia. Namely, based on specific design program, tests were conducted during investigation and design of earthfill dam Kozjak on the river Treska, near Skopje. For that goal, direct shear-box was used as shown in Figure 7.

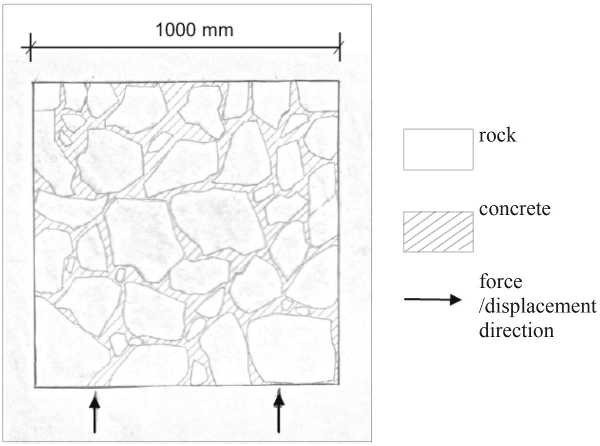


Слика 7 Апарат за директно смицање величине 1,0x1,0x0,60 m примењен у току испитивања
Figure 7 Direct shear box 1,0x1,0x0,60 m applied during the testing

The original version is with size 1,50x1,50x0,60 m, but it was modified to dimensions 1,0x1,0x0,60 m in order to establish conditions for appliance of higher normal stresses. The shear surface is horizontal (it is positioned in the middle between the lower and the upper frame of the shear box), the normal stress is achieved with 4 vertical presses from 1000 kN, and the horizontal load (shear stress) is achieved with two inclined hydraulic presses mounted under an angle of about 11° related to horizontal plain. The lower frame is static, while the upper frame is moving over it using rollers which help to restrict unwanted resistance from any kind. Usually, coarse-sized material used in embankment bodies is compacted under certain conditions in the whole height of the box, after which a testing procedure with known methodologies for shearing is applied.

In this case, a specific treatment of the contacts is applied, where modeling of the bedrock is done in the lower frame of the shear box (Figure 8), where data from geological mapping is used for the conditions of the rock. The most present scale and type of fracturing in the diversion tunnel is adopted, given through the number of monoliths on 1 m^2. The space between the monoliths is filled with concrete. The surface part of the modeled base is with local irregularities which are in the order of ±5-6 mm, with which the roughness of the bedrock under the dam is simulated. It was intended to place the modeled bedrock surface as close as possible to the lower part of the upper frame, in order to secure failure along the contact surface rather than in the materials which are compacted in the upper frame. This way, along with the direct shearing between the interfaces surfaces, the model also allowed continual measuring of the vertical displacements as well. With such disposition the next types of interfaces were investigated:

- bedrock (marbleized limestone) - rockfill;
- bedrock - filter material;
- bedrock - clay.



Слика 8 Скица моделиране стенске основе у доњем раму апарата за директно смицање
Figure 8 Illustration of modeled bedrock in the lower frame of the shear box

After the performed tests with the bedrock, it was removed and replaced with concrete slab in order to conduct testing of the concrete-clay interface.

During the testing of the rockfill material, grain size composition with mix of particles with d≤15cm was adopted, coefficient of uniformity $Cu=d_{60}/d_{10}=11\text{-}14$ and maximal content of fine fraction under 0.6 cm around 8-11%, which corresponds with the confirmed assumptions in practice of similar materials. The filter material was assumed as an average sample of granulometric content from the second filter zone of the dam.

In the current state, the direct shear apparatus allows application of maximal vertical stress of about 1 MPa. There the materials are embedded in two layers with approximate height of the individual layers of 0.15 m. The physical and mechanical parameters obtained during the compaction are shown in the Table 1.

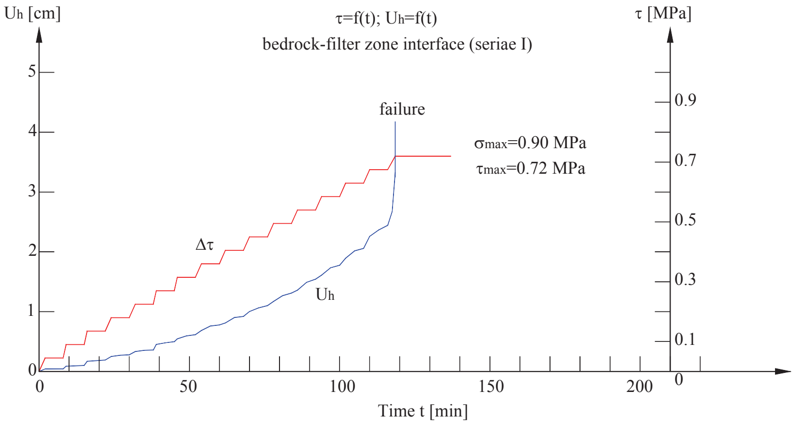
Табела 1 Физичко-механичке карактеристике збијених материјала

Table 1 Physical and mechanical parameters of the compacted materials

Material	Volumetric weight in natural condition	Volumetric weight in dry condition	Water content	Liquid limit	Plasticity limit	Plasticity index
	g [kN/m^3]	g_d [kN/m^3]	w [%]	w_L [%]	w_P [%]	I_P [%]
Rockfill	20,45-21,50	19,70-20,93	2,60-3,74			
Filter	23,28	22,28	4,00			
Clay	17,93-20,22	14,52-16,18	21,46-26,40	43,30	23,30	20,00

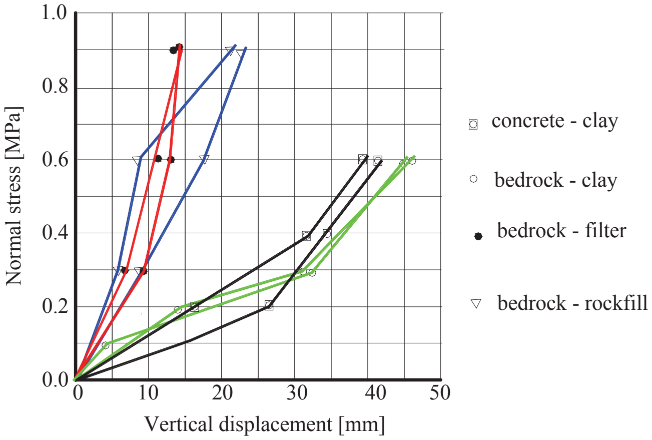
After installation, the material is vertically loaded, with which normal stress is applied over the surface of shearing. This was done in 4 stages, until consolidation of the vertical displacements (Uv) on every stage, as well as during $\sigma_{max.}$ The vertical load was maintained constant for 24 hours. The selection of the intensity of the loading depends upon characteristics of the apparatus i.e. its maximal value. So, for the rockfill and the filter it was adopted σ_{max}=0.9 MPa, while the other loads were interpolated on 0.30 MPa and 0.60 MPa. Because of the expected larger displacements, in the case of clay it was adopted σ=0.20, 0.40 and 0.60 MPa, where at certain points, for control purposes, it was continued up to σ_{max}= 1.0, relatively 0.3 MPa.

After the performed consolidation, a horizontal load was applied also in stages ($\Delta\tau=1/20\sigma_{i,\ max}$), up until provoking failure along the contact surface (bedrock, or concrete-properly installed material). During that, the horizontal displacements (Uh) are permanently registered for every stress step to their consolidation, apropos until failure. Also, during the whole shear process, the vertical displacements are also controlled in order to get complete insight for the testing and the behavior of the material. One example of the adopted stress pattern in the phase of shearing is shown in Figure 9. One experiment in one series consists of three points with proper maximal vertical loading. For all of the materials a total of two series of examinations over the bedrock and two series of clay over concrete base were conducted.

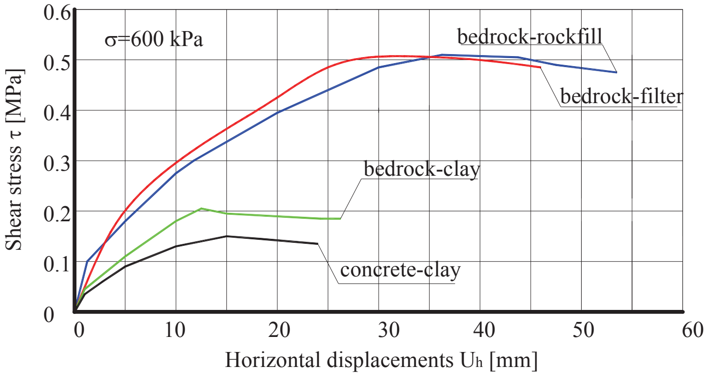


Слика 9 Пример развоја напона у току смицања
Figure 9 Example of stress pattern in the phase of shearing

For illustration of the obtained results, few typical diagrams are shown below. Figure 10 shows diagrams for normal stresses and vertical displacements (σ=f(Uv)) for all interface types, while figure 11 summarizes diagrams for relation shear stress-horizontal displacements (τ= f (Uh)). There an example of same level of vertical stress (σ=0.6 MPa) is chosen, in order to get an insight in the differences among the achieved displacements until failure. It is obvious that failures in rockfill and filter material occur under large displacements, while under much lower for clay.

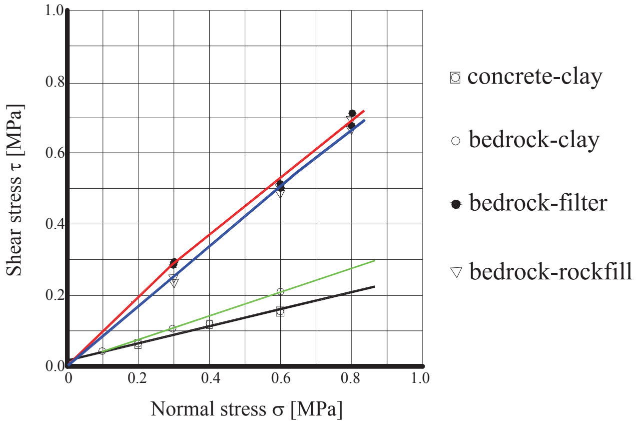


Слика 10 Сумарни дијаграм односа нормални напон-вертикално померање
Figure 10 Summarized diagram of the relation normal stress-vertical displacement



Слика 11 Сумарни дијаграм односа смичући напон-хоризонтално померање за исти ниво нормалног напона
Figure 11 Summarized diagram of the relation shear stress-horizontal displacement under same level of vertical stress

On figure 12, classic diagrams for shear/normal stress relations (τ=f(σ)) are presented. All these diagrams explicitly show the difference in the mechanical behavior of the different contacts, from which it can be concluded that the interface of the filter material and the rockfill with the base give similar relations, while the clay-bedrock and clay-concrete contacts show specific behavior. Typically, the failure time is shortest for the clay, and for same value of σ_{max}, which is very logical and consistent with the properties of the clay in relation to the other materials.

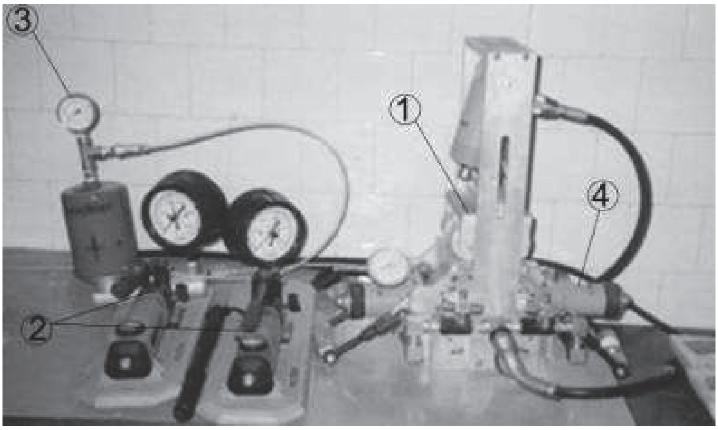


Слика 12 Сумарни дијаграм зависности смичући напон-нормални напон
Figure 12 Summarized diagram of the relation shear stress-normal stress

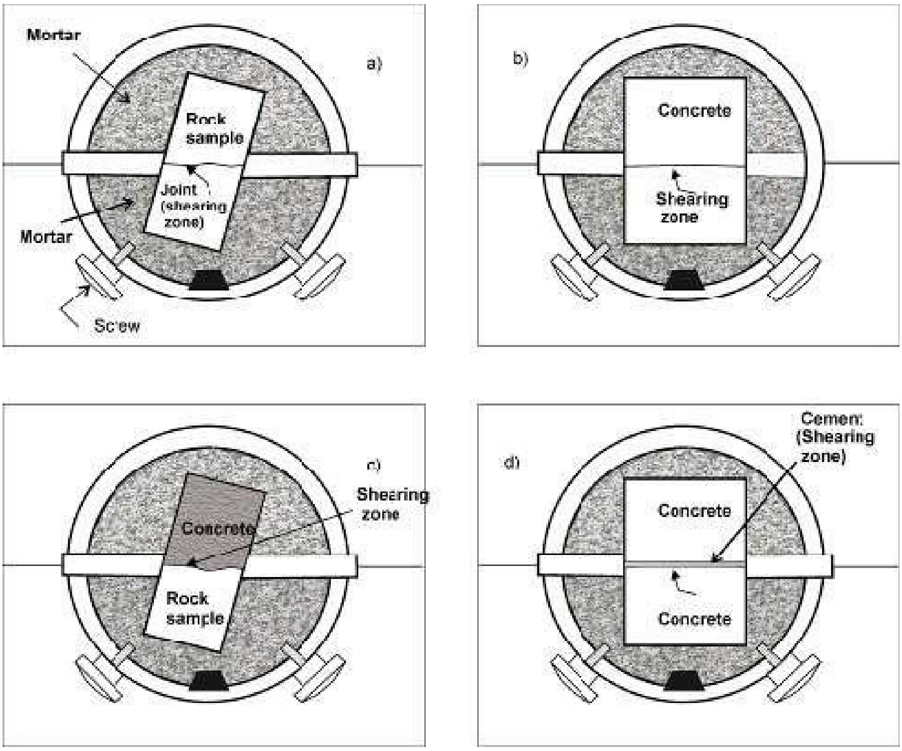
ONE METHODOLOGY FOR PHYSICAL MODELING OF INTERFACE SHEAR STRENGTH AT ARCH DAMS

The specific construction of concrete arch dams require special attention and knowledge of shearing parameters on the interface concrete-rock mass at the zone of foundation, but also at the zones of radial joints filled with grouting cement mixture at the arch dam body. Usually these parameters are examined in situ, with pressing and shearing of concrete blocks and rock mass. This kind of tests was also conducted for the needs of designing of arch dam Sv.Petka on the river Treska, near Skopje, which is already built.

However, it is well known that the performing of this type of tests is very hard, and these investigations are very rare in the phase before Preliminary design, when one of the key questions should be answered: the selection of dam type! Having this in mind, during the preparing of the program for mechanical investigations for this dam, the authors came out with an idea to use the so called Hoek-box for the investigation of the properties on the concrete-rock mass interface (Figure 13). This box is usually used for testing shear strength along discontinuities (fractures), and as far as is known by the authors, it has been used for the first time by the Chair of Geotechnics at the Faculty of Civil Engineering in Skopje in 2002 for investigation of interface shear strength between different materials. Further application is presented by Mitovski (2015). So, the main physical models (three of them developed by authors) that can be used in this box are presented in Figure 14.



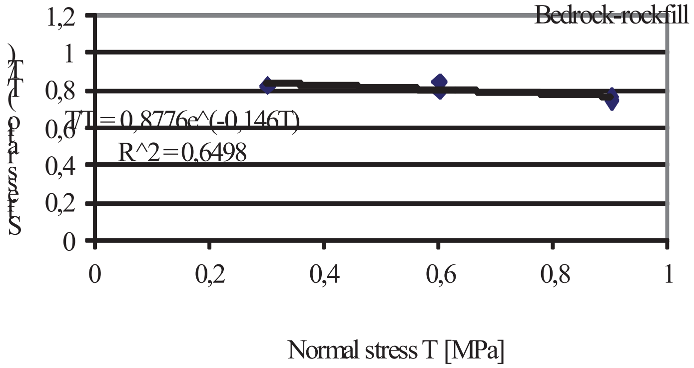
Слика 13 Хекова кутија за директно смицање за испитивање смичуће чврстоће дуж дисконтинуитета стена: (1) кутија за постављање узорака (сагласно шеми датој на слици 14); (2) хидрауличке пумпе; (3) ћелија за притисак; (4) пумпа за нормални и смичући напон
Figure 13 Hoek direct shear box for testing of shear strength of rock discontinuities: (1) box where the samples are installed (see scheme in Figure 14); (2) hydraulic pumps; (3) pressure cell; (4) pump for normal and horizontal load



Слика 14 Физички модел смичућих опита у Хековој кутији за директно смицање
Figure 14 Physical model for shear tests in Hoek direct shear box

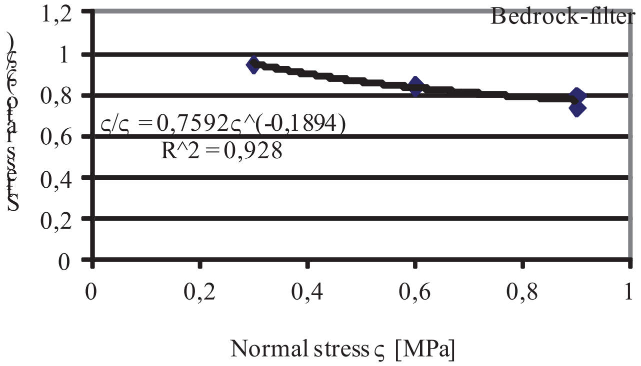
ANALYTICAL MODELING OF INTERFACE SHEAR STRENGTH

The further logical step in all performed analyses is to find analytical connection between parameters during shearing along interfaces. In relation to the shearing strength parameters at the Kozjak earthfill dam contacts, certain non-linearity is noticed in all of the conducted cases, which is illustrated in $\tau/\sigma=f(\sigma)$ diagrams. These diagrams show that the influence of the level of the normal effective stress (σ) is very important, especially for the interface rockfill-bedrock. Some of the results are presented in the following figures.



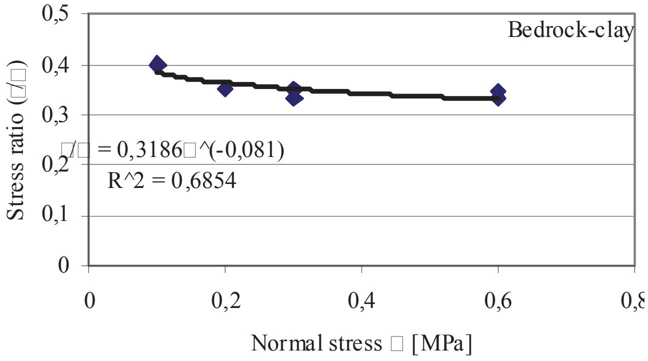
Слика 15 Зависност τ/σ=f(σ) за контакт основна стена-камени набачај (сумарни дијаграм за две серије)

Figure 15 Relation τ/σ=f(σ) for interface bedrock-rock fill (summarized diagram for two series)

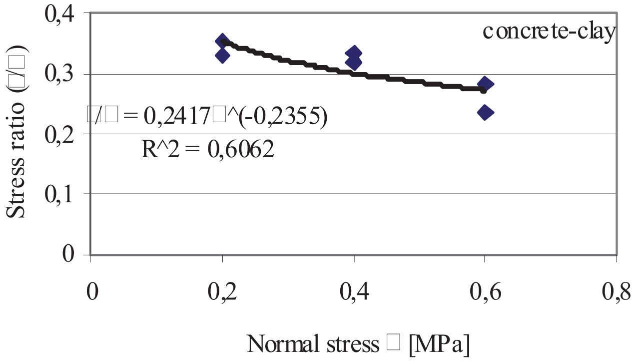


Слика 16 Зависност τ/σ=f(σ) за контакт основна стена-филтер (сумарни дијаграм за две серије)

Figure 16 Relation τ/σ=f(σ) for contact bedrock-filter (summarized diagram for two series)

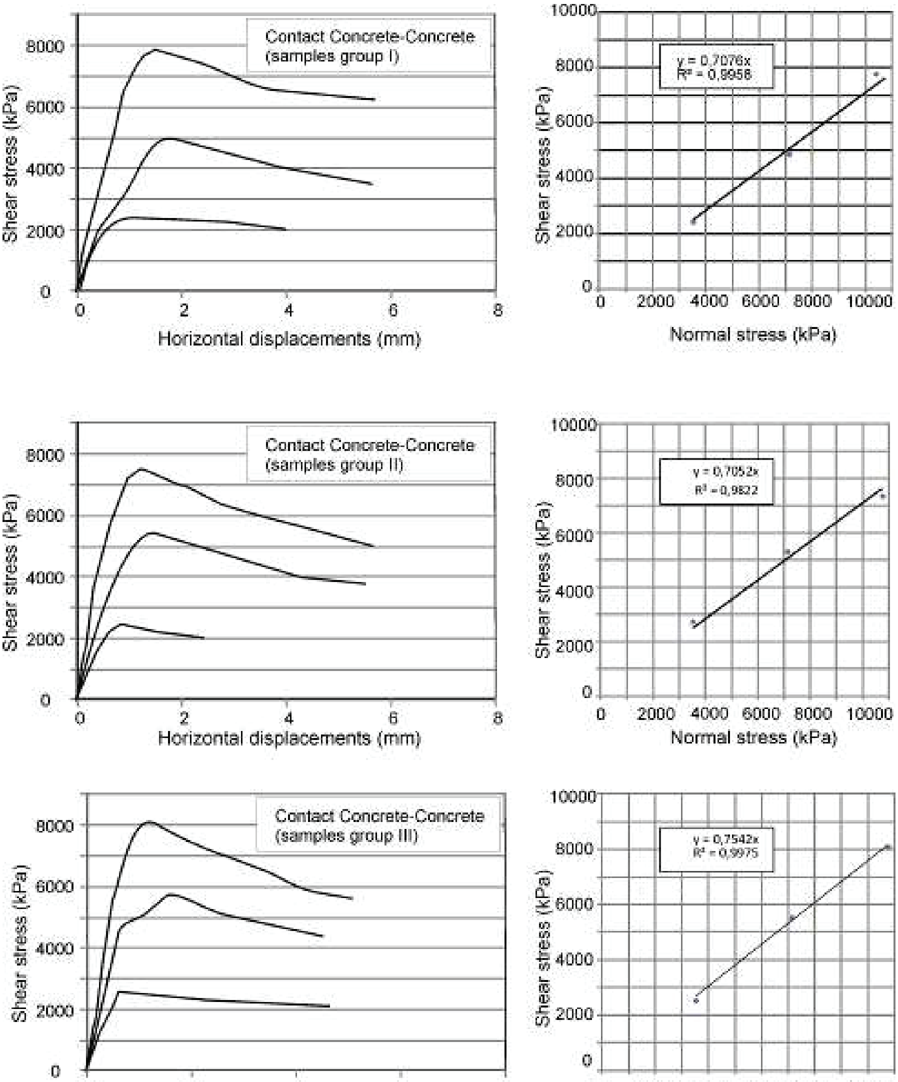


Слика 17 Зависност τ/σ=f(σ) за контакт основна стена-глина (сумарни дијаграм за две серије)
Figure 17 Relation τ/σ=f(σ) for contact bedrock-clay (summarized diagram for two series)



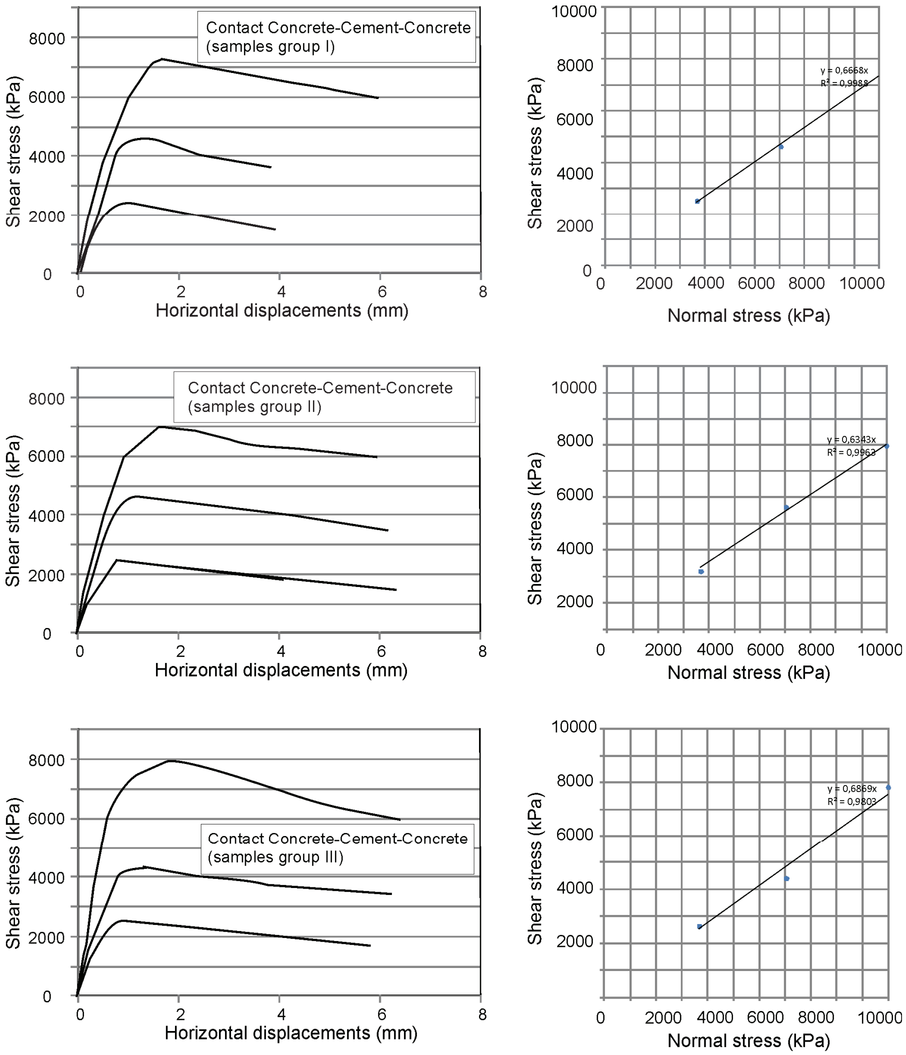
Слика 18 Зависност τ/σ=f(σ) за контакт бетон-глина (сумарни дијаграм за две серије)
Figure 18 Relation τ/σ=f(σ) for interface concrete-clay (summarized diagram for two series)

Summarized analytical relations established during interface shear tests on models shown in Figure 14, are presented in Figures 19 and 20. The tests are conducted for wide spread domain of normal stresses. The relations τ/σ for peak condition of the friction indicates close range of values for interface shear strength for all cases of contact concrete-concrete, while a little bit lower values are for a case of contact concrete-cement-concrete. Diagrams for horizontal deformations indicate that the failure is for displacements values between u=4-7 mm before the limit strength, and achieved friction is with some amount of lowering in the shear stress after peak values.



Слика 19 Сумарни дијаграми за зависности између смичућег напона и хоризонталних померања и нормалног и смичућег напона за контакт бетон-бетон

Figure 19 Summarized diagrams as a relation between shear stress and horizontal displacements and normal stress vs. shear stress for interface concrete-concrete



Слика 20 Сумарни дијаграми за зависности између смичућег напона и хоризонталних померања и нормалног и смичућег напона за контакт бетон-цемент-бетон
Figure 20 Summarized diagrams as a relation between shear stress and horizontal displacements and normal stress vs. shear stress for interface concrete-cement-concrete

Analyzing the obtained data, the authors are at the opinion that the applied methodologies have a lot of advantages, as well as some limitations which are out of the scope of the paper, but however deserve scientific occupation and challenge for future analyses.

CONCLUSION

Knowing of the interface shear strength parameters is of great importance, so the development of methodologies for investigation presents a great challenge for scientific research. Authors stress out that investigations on physical models should always be conducted for all significant structures, which will further be analyzed analytically and numerically in order to get a real picture of the behavior of the system in interaction: artificial structure (dam)-foundation (geological setting).

Having in mind the obtained results, authors think that the methodologies can be very convenient for implementation. In combination with the established methods, there are possibilities for comparison of the obtained results and extrapolation of the parameters in areas which are in the same range of size as is the structure. Prerequisites for real stress-deformation analyses and successful designing of large structures are created that way.

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