NUMERICAL MODELING OF ZONED ROCKFILL DAM DURING CONSTRUCTION CONSIDERING GRANULAR INTERFACE BEHAVIOR

B. Pardoen [1] and J.-M. Konrad [2]

Abstract

The behaviour of interfaces between granular materials in zoned embankment dams can influence their overall behaviour. Soil-structure interfaces have been largely studied but only a few analyses of interfaces between the granular materials composing rockfill dams have been realised. Consequently, there is a need to consider the influence of material interfaces within dams. A numerical modelling of a rockfill dam is performed to simulate its mechanical behaviour during the construction phase. The behaviour is analysed based on the numerical methods used to model the interfaces and on interface characteristics, through sensitivity analyses. A particular attention is paid to the influence of interface shear strength on the dam shear deformations, settlements, and plasticity. The numerical results highlight that the contact condition and the interface characteristics influence the dam behaviour. Low shear resistance of interface engenders an increase of relative displacements, settlements, and shear strains in the dam. Moreover, the dilative behaviour of the interfaces also affects the dam overall behaviour.

Keywords: Rockfill dams, interfaces, granular materials, mechanical behaviour, numerical modelling.

INTRODUCTION

The behaviour of kinematic discontinuities in dams is important to consider in order to better simulate the dam overall behaviour. Various studies have been conducted on the behaviour of soil-structure interfaces in dams (Khalid et al. 1990; Zhang and Zhang 2009). However, only a limited number of studies have been realised to characterise the contacts between granular materials in earth core rockfill dams (Hu et al. 2010; Tanchev 2014; Zhang et al. 2008). Zoned rockfill dams are composed of granular materials having different characteristics. The granular interfaces are of type soil-soil or soil-rock and have not been studied extensively. Therefore, there is a need to study the influence of granular interfaces on the prediction of the dam behaviour.

A numerical study of a zoned rockfill dam is realised to simulate its mechanical behaviour during the construction phase. The dam behaviour is studied mostly regarding its deformations, strength, and the stress transfers. Different types of interfaces are considered and sensitivity analyses are performed. The approach aims for two main contributions. The first is to evaluate how the behaviour of soil interfaces influence the overall behaviour of dams. The second is to highlight what particular characteristics of interfaces affect significantly the dam behaviour. The developed approach is numerical and highlights the simulated behaviour of a rockfill dam.

ZONED ROCKFILL DAMS

Embankment dams are the most frequently constructed large dams. Among them, earth core rockfill dams (ECRD) are generally constructed according to the structure schematically presented in Fig. 1 for dams having a vertical core. They are composed of granular materials and rockfill having different functions. Generally, four material zones compose the dams (Fig. 1) with increasing granulometry towards the outside. The materials are (Tanchev 2014): a central compacted core of fine material ensuring the water impermeability, a filter material (sand or gravely sand), a transition material (sandy gravel), and the embankment. The latter is composed of coarse and permeable rockfill that ensures the stability. Furthermore, interfaces between these granular materials exist at their contacts and require further study.

The materials are deposited by successive layers and compacted during the construction phase. The maximal thick-

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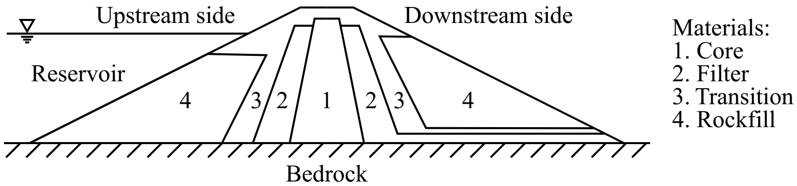


Figure 1. Schematic representation of a cross-section in a zoned rockfill dam.

ness are often of 50 cm for the internal materials and 1 to 2 m for the external rockfill (Tanchev 2014). Usual values of the slopes of the material zones can be found in (Tanchev 2014). The height of embankment dams can reach 100 m to 300 m for very large dams.

MECHANICAL MODELLING OF INTERFACE

The mechanical modelling of interfaces is described hereafter. Firstly, the numerical methods used for the interface modelling are developed. Secondly, the constitutive models of materials and interfaces are defined.

Numerical Methods

Kinematic discontinuities at interface can be represented by different numerical approaches as direct contact, thin layers, joints, or interface elements (Cerfontaine et al. 2015; Cescotto and Charlier 1993; Day and Potts 1994; Gens et al. 1990; Sharma and Desai 1992; Zhang and Zhang 2009). Hereafter, a finite difference method is used and allows to represent glued and unglued interfaces.

A glued condition implies the compatibility of the displacements between adjacent materials (Khalid et al. 1990). Consequently, relative normal and tangential displacements are not allowed; which can lead to an increase of load and stress transfers across the interface (Khalid et al. 1990). It is often modelled by a direct contact or by thin interface layers (Sharma and Desai 1992). An unglued condition permits relative normal and tangential displacements at interface. It can be of interest especially for adjacent materials exhibiting large disparities of properties. The interface zero-thickness elements belong to this category of methods (Cerfontaine et al. 2015; Cescotto and Charlier 1993; Day and Potts 1994).

Constitutive Material Model

The behaviour of glued interfaces is directly related to the behaviour of the two adjacent materials. It requires to define the behaviour of the granular materials composing rockfill dams. The material behaviour is represented by a non-associated elastoplastic internal friction model with linear elasticity and perfect plasticity. A Mohr-Coulomb yield criterion is considered:

$$\tau_y = c + \sigma \ tan\phi \tag{1}$$

where τ_y is the shear (yield) strength, c is the cohesion, σ is the normal stress, and ϕ is the internal friction angle. The strain and stress fields are defined positive under compressive regime following the soil mechanics convention.

A non-associated framework is considered for the plastic flow. It introduces the material volumetric behaviour with the dilatancy angle ψ (Bolton 1986). The latter is related to the friction angle ϕ and to the critical (residual) friction angle ϕ_c by the following relation (Bolton 1986):

$$\phi = \phi_c + \psi \tag{2}$$

The critical state corresponds to a stable state towards which a soil evolves under large shearing. At this state, plastic shearing occurs without volume variation.

Constitutive Model of Interface Elements

The mechanical behaviour of zero-thickness interface elements is described by stress-strain relations in their tangential and normal directions (Cerfontaine et al. 2015). Hereafter, the superscript ^{i} denotes quantities related to interfaces. The $_s$ and $_n$ subscripts correspond to the tangential and normal directions to the interface.

The behaviour of interfaces can be: open without contact, close and sticked, or close and unsticked. The open state occurs for interface under tensile or dilatant behaviour which corresponds to a relative normal displacement $\Delta u_n^i < 0$ between the two interface's sides. If no tensile strength is considered between the grains (as for non-cohesive materials) the normal and shear stresses in the interface are null $\sigma^i = \tau^i = 0$. The close states are called "stick-slip" (Fig. 2 (b-c)) and correspond to a penetration distance $\Delta u_n^i \geq 0$. A plastic relative tangential displacement (interface slipping) is not allowed $\Delta u_s^{i,p} = 0$ for the sticked-close state (elastic state). It is allowed $\Delta u_s^{i,p} \neq 0$ under plastic state for the unsticked-close state (elastoplastic strain). Moreover, the interfaces in embankment dams often behave as compressed contacts or closed interfaces because of the material dead weight (Tanchev 2014).

For the elastic stick state, the stress-strain behaviour is expressed in a rate form as:

$$\begin{bmatrix} \dot{\sigma}^i \\ \dot{\tau}^i \end{bmatrix} = \begin{bmatrix} K_n & 0 \\ 0 & K_s \end{bmatrix} \begin{bmatrix} \Delta \dot{u}_n^{i,e} \\ \Delta \dot{u}_s^{i,e} \end{bmatrix} \tag{3}$$

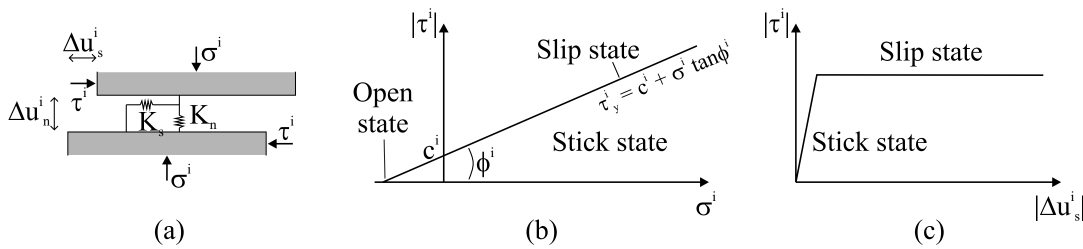


Figure 2. Interface behaviour with a Mohr-Coulomb yield criterion: (a) schematic representation, (b) shear strength with stick-slip states, and (c) shear stress-displacement curve.

where τ^i and σ^i are the interface shear and normal stresses, $\Delta u_s^{i,e}$ and $\Delta u_n^{i,e}$ are the interface elastic relative displacements in the tangential and normal directions. Eq. 3 depends on the elastic stiffness moduli in both directions, K_s and K_n (Fig. 2 (a)).

The stress-displacement behaviour of interfaces is either linear or non-linear depending on the type of contact. The elastic stiffness moduli are therefore considered as constant or not. For K_n, a dependence to the interface opening is often considered (Alonso et al. 2013; Gens et al. 1990). K_s can be expressed with hyperbolic stress-dependent relations (Hu et al. 2010; Tanchev 2014; Xu et al. 2012). Nevertheless, assessing the interface behaviour requires experimental investigations. Unfortunately, such investigations are seldom available for granular interfaces. The stiffness moduli are therefore assumed constant. Moreover, high values of K_n are often chosen to limit the interface interpenetration.

The transition from elastic stick to elastoplastic slip states is governed by an interface yield criterion. It represents the shear strength of the interface τ_y^i (Fig. 2 (b)). Various yield criteria exist for rock joints depending on their roughness (Barton 1973; Goodman et al. 1968; Patton 1966). Nevertheless, the behaviour of granular interfaces subjected to shearing can be related to the behavior of granular materials. The contact is therefore governed by grain friction and grain rearrangement, which leads to volumetric deformation (Hu et al. 2010; Zhang et al. 2008). For simplicity reason, a non-associated perfect plasticity model with Mohr-Coulomb's yield criterion is regularly adopted to represent the shear strength of interface:

$$\tau_y^i = c^i + \sigma^i\ tan\phi^i \tag{4}$$

where c^i is the cohesion and ϕ^i is the friction angle of the interface. Fig. 2 (b-c) details the interface shear behaviour.

Furthermore, the volumetric behaviour is governed by the normal stiffness modulus K_n and by the interface dilatancy angle ψ^i. K_n governs the interface closing and interpenetration (contractive behaviour) while ψ^i allows volumetric deformations under plastic shearing.

NUMERICAL MODELLING OF A ZONED ROCKFILL DAM DURING CONSTRUCTION

A large scale numerical study of a rockfill dam is realised to simulate its mechanical behaviour during the construction phase. The objective is to analyse the influence of granular interfaces on the dam behaviour. The latter is analysed mostly regarding the settlements, stress transfers, shearing, and plasticity development. The different types of interface detailed previously are considered and sensitivity analyses are performed. The latter allow to highlight the particular characteristics that modify the dam behaviour. The numerical results illustrated in the following figures detail the dam and interface behaviours at the end of the construction phase.

Numerical Model

The mechanical modelling is realised in two-dimensional plane strain state. The rockfill dam which is considered is a theoretical zoned dam having the geometry and the material properties similar to large dams in Québec (Hydro-Québec projects). An explicit finite difference method (FDM) is used with FLAC software.

Mesh and conditions

A representation of the numerical model is illustrated in Fig. 3 with the mesh and the boundary conditions. The dam is 100 m high, has a total ground extension of 380 m, and is founded on a flat rigid bedrock. The material slopes are defined according to usual values available in Tanchev (2014). Only half of the dam is considered for symmetry reason during the construction phase and is composed of 3000 elements. The normal displacements are blocked along the symmetry vertical y-axis to establish the symmetry and along the horizontal x-axis to represent a non-deformable bedrock.

The modelling of the construction phase is realised by reproducing the successive deposition of horizontal layers having a thickness of 1 m. The initial conditions in the materials at deposition is a homogeneous nil stress state: $\sigma_{xx,0} = \sigma_{yy,0} = \sigma_{xy,0} = 0\ kPa$. For each layer, the materials are allowed to settle under their own dead weight

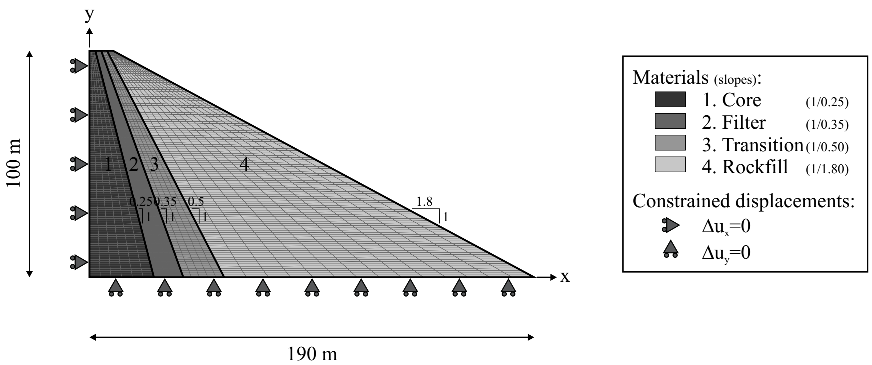


Figure 3. Schematic representation of the model used for the numerical modelling of the rockfill dam.

due to gravity effect before the deposition of the next layer. The gravity effect engenders stress redistribution in the dam for each additional material layer. Different authors showed the importance and validity of a layered numerical construction (Cathie and Dungar 1978; Clough and Woodward 1967; Tanchev 2014).

Elastoplastic parameters

The elastoplastic parameters for the materials are detailed in Table 1 and correspond to values commonly used for the considered materials. The values are defined based on the materials of the LG-2 rockfill dam in Québec (Touileb et al. 2000). The dam has an impervious core made of moraine (glacial till).

Shear resistance is considered but no tensile strength is assumed between grains and rock blocks. This is the case for non-cohesive granular materials in embankment dams and especially for coarse materials. Moreover, the dilatancy angles in Table 1 are derived from Eq. 2 and from the values of ϕ_c.

Glued Interfaces with Direct Contact

The interfaces between the materials of the dam are firstly considered as being glued direct contacts with displacement compatibility.

Reference case

The numerical results obtained at the end of the construction are detailed in Figs. 4 and 5 for the parameter values of Table 1. Fig. 4 details the dam overall behaviour and Fig. 5 details the behaviour along a horizontal cross-section at mid-height (y = 50 m). The interfaces between the materials are indicated on both figures to highlight the impact of interfaces and property transitions. These modelling results consist of a reference case before performing sensitivity analyses.

A first result to notice in Fig. 4 (a) is that the dam is globally in elastic state at the end of the construction phase. During the simulation of the construction, a plastic flow often appears at the deposition of each material layer at a nil stress state. This occurs because materials are non-cohesive. Then, the stress distribution evolves due to gravity effect and only a few elements are in plastic state at the end of the construction.

The plasticity develops mainly in some parts of the filter and transition materials at about mid-height. The strength parameters (ϕ and c) of the different materials are similar but their Young's moduli E are different. A stiffer behaviour leads to higher stresses for the same strain level. Thus, plasticity is more prone to appear in the filter and transition materials. Nevertheless, the dam overall behaviour is elastic and an elastic modelling has shown similar results in comparison to the elastoplastic simulation. It implies that the dam overall behaviour is dominated by the elastic properties of the materials.

The displacements in the dam are detailed in Figs. 4 (b-c) and 5 (a). The horizontal displacements Δu_x correspond to an overall movement towards the exterior of the dam. Their amplitude is low in comparison to the settlements Δu_y. For the latter, a larger settlement is observed in the central till core with a maximal settlement of 59 cm at mid-height. This simulated behaviour is consistent with field measurements performed in rockfill dams. For instance, measurements of settlements by inclinometers were performed during the construction of the SM-3 rockfill dam in Québec. The measurements indicated a maximal settlement of 65 cm at the mid-height of the dam for 100 m of construction height (Hydro-Québec 2010). In a synthesis of observed and modelled settlements, Tanchev (2014) mentioned largest values at dam's mid-height in the central zone. The values ranged between 20 and 110 cm depending on the dam size and type.

Furthermore, the filter and transition materials deform slightly less than the other materials due to their higher elastic stiffness. This is visible on the simulated displacement results in Fig. 4 (b-c) and along the cross-section in Fig. 5 (a). On this figure, the horizontal displacement and the displacement norm $||\Delta u|| = \sqrt{\Delta u_x^2 + \Delta u_y^2}$ are also indicated. The amplitude of the horizontal displacements is relatively

Table 1. Elastoplastic material parameters

Symbol	Name	Core	Filter	Transition	Rockfill	Unit
γ_d	Dry weight density	21	20.6	20	21.2	kN/m^3
E	Young's modulus	50	90	80	50	MPa
ν	Poisson's ratio	0.3	0.35	0.3	0.25	$-$
c	Cohesion	0	0	0	0	MPa
ϕ	Friction angle	37	44	43	45	$^\circ$
ϕ_c	Critical (residual) friction angle	32	32	32	35	$^\circ$
ψ	Dilatancy angle	5	12	11	10	$^\circ$

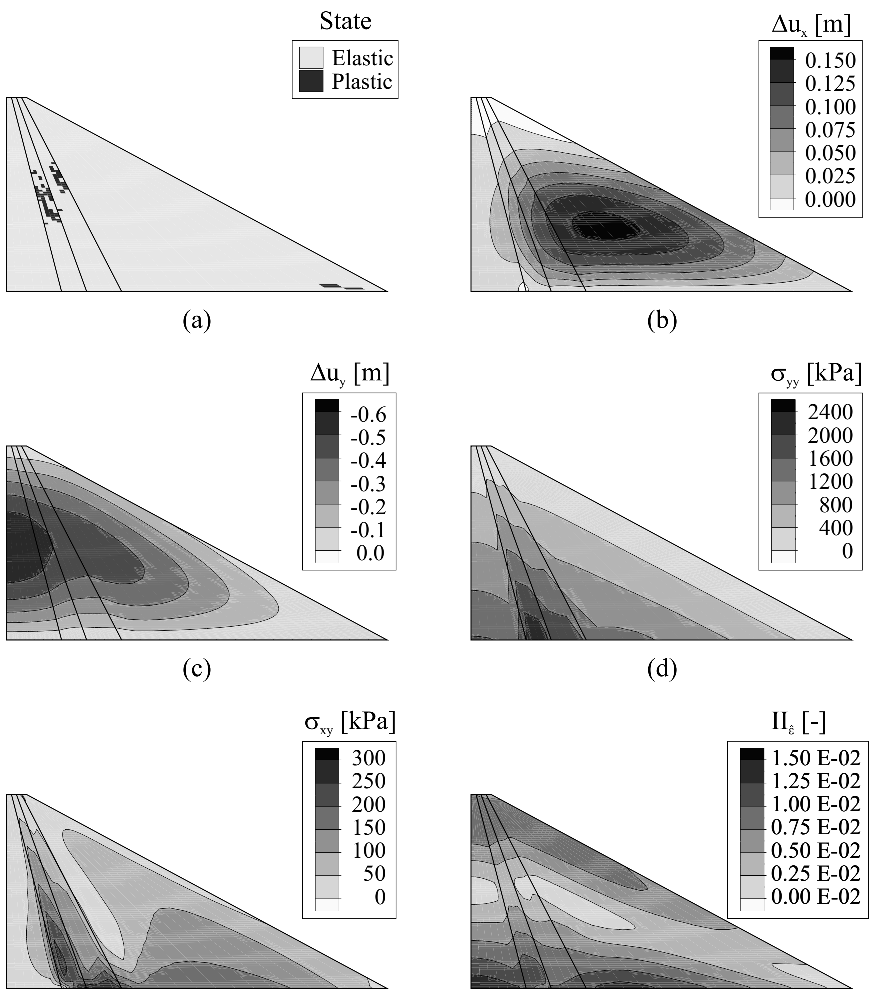


Figure 4. Dam behaviour for glued interfaces with direct contact: (a) plastic state, (b) horizontal displacements, (c) settlements, (d) vertical stress, (e) shear stress, and (f) equivalent deviatoric strains in the dam.

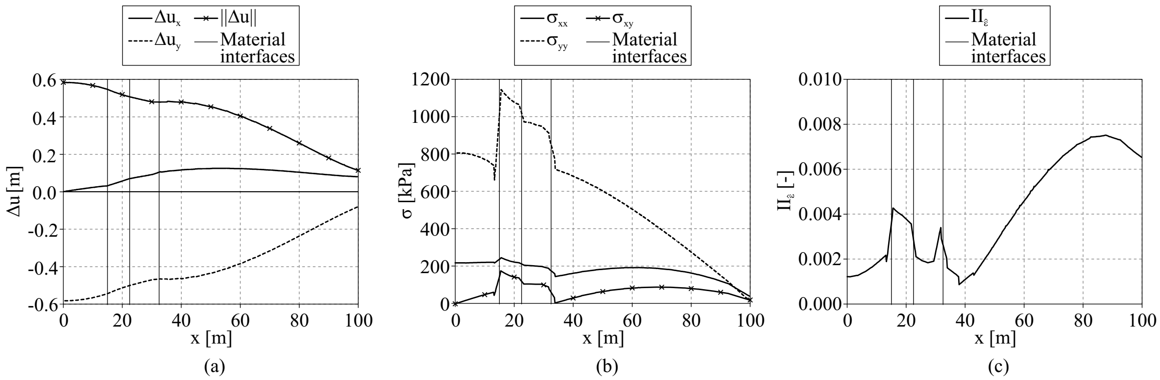


Figure 5. Dam behaviour for glued interfaces with direct contact: (a) displacements, (b) stresses, and (c) equivalent deviatoric strains along a horizontal cross-section at mid-height.

low compared to the settlement; therefore, the amplitude of $||\Delta u||$ is similar to the amplitude of the settlement. Besides, the total deformations are mainly composed of elastic deformations.

Figs. 4 (d) and (e) illustrate the vertical and the shear stresses (σ_{yy} and σ_{xy}). Normal stresses are positive in compression and shear stresses are positive for clockwise shearing. The computed stresses are more important in the stiffer materials, especially in the filter material. Fig. 5 (b) helps to highlight the variation which is observed when crossing the material interfaces.

Furthermore, Figs. 4 (f) and 5 (c) present the second invariant of the deviatoric strain tensor $II_{\hat{\varepsilon}}$. It is an equivalent deviatoric total strain, i.e. a scalar shear amplitude, expressed as:

$$II_{\hat{\varepsilon}} = \sqrt{\frac{1}{2}\hat{\varepsilon}_{ij}\hat{\varepsilon}_{ij}} \tag{5}$$

where $\hat{\varepsilon}_{ij}$ is the deviatoric part of the total strain tensor ε_{ij}:

$$\hat{\varepsilon}_{ij} = \varepsilon_{ij} - \frac{\varepsilon_{kk}}{3}\ \delta_{ij} \tag{6}$$

Here as well, variations of $II_{\hat{\varepsilon}}$ across the different materials are observed in the simulated results.

The different variations in the above results highlight that property transitions and material interfaces have an impact on the overall behaviour of the dam. They require further investigations to better understand their influence. Consequently, different sensitivity analyses are realised hereafter on the material and interface properties. The objective is to determinate what properties affect the dam behaviour.

Influence of material properties

Analyses of the material characteristics are performed to highlight if their variations could influence the dam behaviour. The previous simulation has shown some effects of the elastic properties. Hereafter, the analysis of Young modulus variations is extended by considering a stronger gradient between the materials. From the reference case, several values of E are tested for each material. These values are chosen in acceptable range (between 40 and 150 MPa) for the considered materials. Identical values are kept for the other elastoplastic characteristics (Table 1).

The numerical simulations indicate that the reduction of a material elastic modulus causes an increase of the settlements. This occurs especially in the considered material zone but also in the other zones because of the displacement compatibility imposed at the interfaces (glued condition). In contrast, higher values of stiffness reduce the settlements of the dam, increase the stresses, and lead to a larger development of plasticity in the materials.

The development of plasticity is exhibited in Fig. 6 for an independent increase of each material's Young modulus up to a value of 150 MPa. The plastic and elastic states can be compared to the reference case in Fig. 4 (a). For each simulation, a larger development of plasticity clearly appears in the considered material zone (Fig. 6 (a-c)) unless in the rockfill (Fig. 6 (d)). The results indicate that plasticity is reached in each zone almost at the end of the construction. It engenders an increase of plastic deformations and of shearing (σ_{xy}, $II_{\hat{\varepsilon}}$). The latter occurs in the plastic material but also at its interfaces with the other materials. Furthermore, the numerical results indicate that strong stiffness gradients between the materials can engender differential settlements between them.

A sensitivity analysis of the variation of the plastic shear strength is also realised for each material. It is done by reducing ϕ to its critical value ($\phi = \phi_c$ and $\psi = 0$). The numerical results have highlighted that the variability of ϕ has less impact on the dam behaviour than the variability of E, for the considered values.

From these sensitivity analyses, it can be said that the material properties can influence the dam behaviour, especially

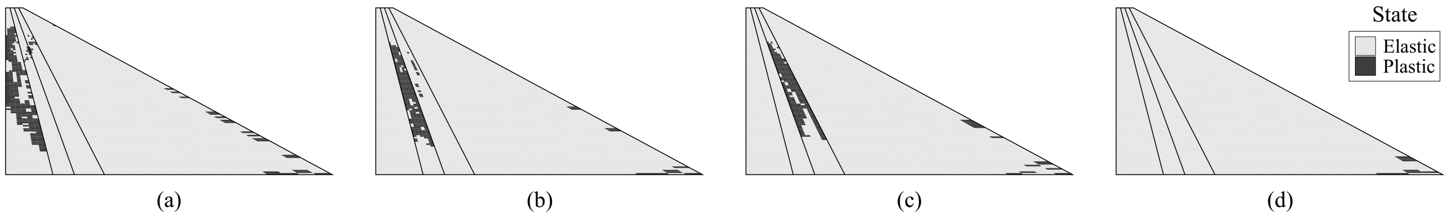


Figure 6. Influence of E on the development of plasticity in the dam for glued interfaces with direct contact: (a) E_{core}, (b) E_{filter}, (c) $E_{transition}$, and (d) $E_{rockfill}$ fixed at 150 MPa.

if they lead to the development of plasticity close to the interfaces. It can engender an increase of interface shearing, dam settlement, and differential settlements. Nonetheless, glued interfaces do not allow relative displacements at the material contact and can magnify load transfers. Testing other types of interface is therefore necessary to better analyse their influence on the dam behaviour.

Glued Interfaces with Thin Layers

The glued interface type can also be represented by thin material layers. Thin layers of 50 cm thick are added between the materials for all interfaces. Their behaviour is governed by the same constitutive model than the materials (see Table 1 for the material parameters). Two cases are considered for the interface properties: either they correspond to the adjacent materials, or they are reduced to simulate interfaces with lower resistance.

For the first case, considering that all interface's elastoplastic properties correspond to the average properties of the adjacent materials does not affect the dam behaviour. It only reduces the plasticity development in the dam at the end of the construction. In fact, all materials are in elastic state at the end of construction. This was not the case for the reference case with direct glued contacts (Fig. 4 (a)).

The second case simulates the influence of a reduction of interface resistance. Reductions of the elastic stiffness or of the shear strength are considered in all thin layers. From the average values of the adjacent materials, all the interface elastic moduli E^i are reduced by 2 orders of magnitude or all the interface friction angles ϕ^i are reduced to their critical values ($\phi^i = \phi^i_c$ and $\psi^i = 0$, with ϕ^i_c kept constant). It has to be mentioned that the simulated reduction of E^i is strong with all $E^i < 1\ MPa$. It corresponds to a theoretical modification that will highlight the effect of an important loss of elastic stiffness at the interfaces. The modification of the plastic parameters simulates an evolution of the material shear strength in the interface towards its residual value at critical state.

The results at the end of the construction phase are detailed in Fig. 7 along the horizontal cross-section located at mid-height of the dam. They are presented in comparison to the reference case with glued interfaces and direct contacts. It appears clearly that low interface stiffness or shear strength has a strong influence on the dam behaviour. It increases the rockfill settlement and the variation of settlements across the interfaces (Fig. 7 (a)). The equivalent deviatoric total strains $II_{\hat{\varepsilon}}$ in the vicinity of the interfaces are also increased significantly (Fig. 7 (b)).

These results show an important effect of a loss of elastic stiffness in the interfaces leading to an increase of settlements and deviatoric strains. The influence of shear strength is similar but less pronounced because the considered reduction is proportionally less important than the reduction of elastic stiffness. Concerning the development of plasticity, neither of the two resistance reductions modify significantly the plasticity in the dam at the end of construction. The material zones of the dam remain elastic; however, a part of the thin interface layers become plastic when their shear strength is reduced.

Unglued Interface with Interface Elements

Previously, the material contacts have been considered as glued which implies displacement compatibility. Testing an unglued condition is required for a deeper analysis of the influence of material interfaces. Thus, the unglued condition is modelled with zero-thickness interface elements that allow opening and slipping between the materials.

Interface behaviour

The elastoplastic behaviour of interface elements has been described in the section *"Constitutive Model of Interface Elements"* and the chosen parameters are described hereafter. The stiffness modulus values for granular contact have not been extensively reported in the literature. For the normal stiffness K_n, a high value is regularly chosen to limit the interpenetration of the two interface sides. For rock joints, values of shear and normal stiffnesses ranging from 10 to 100 MPa/m are typical of soft joints (Fairhurst 1993). Higher values of normal stiffness of 1 to 10 GPa/m are used for rock joints and concrete-gravel interfaces by Gens et al. (1990) and Xu et al. (2012). For dam interfaces, values largely superior to the material Young's modulus are mentioned by Tanchev (2014) assuming no normal deformation of interface. Hereafter, a constant value of $K_n = 100\ MPa/m$ is

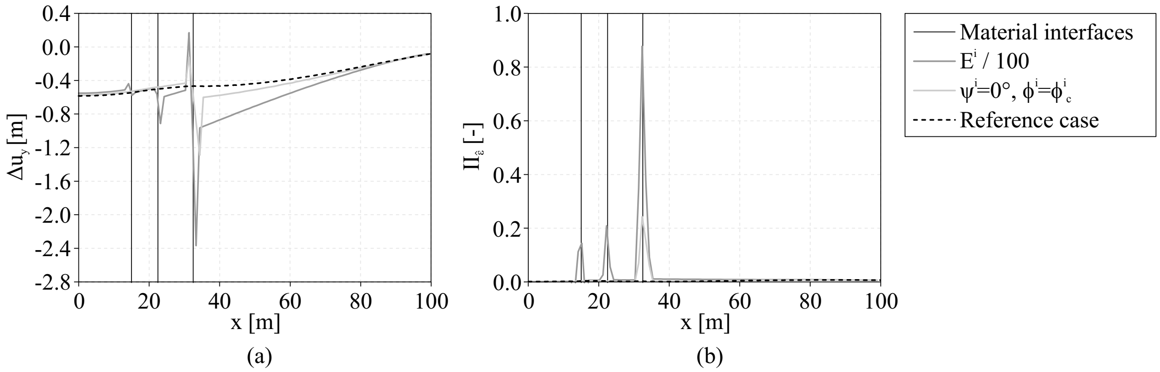


Figure 7. Influence of interface stiffness E^i and shear strength ϕ^i in thin interface layers on the dam behaviour: (a) settlements and (b) equivalent deviatoric strains along a horizontal cross-section at mid-height.

chosen for all interfaces assuming that a slight interpenetration is allowed for contacts between granular materials.

The tangential stiffness K_s conditions the tangential displacements at interfaces. A low value will allow interface slipping while a high value will limit it. Values between 1 and 100 MPa/m are mentioned by Xu et al. (2012) for rockfill–concrete slab joints and lower values are mentioned by Tanchev (2014) for interfaces in dams. A constant value of $K_s = 10\ MPa/m$ is considered for all interfaces to allow interface slipping.

Concerning the plastic behaviour, only a few studies have been conducted to characterise the interfaces between granular materials up to the rupture. Hu et al. (2010) and Zhang et al. (2008) have performed laminar simple shear tests on filter and core soils coming from a zoned rockfill dam. The results indicate that the interface behaviour is dictated by the less resistant material in contact. This has been highlighted by evaluating the strength characteristics of granular interfaces and by observing that cracks and rupture appear preferentially in the weaker material (Hu et al. 2010).

Following the latter studies, the shear strength of interface elements is governed by a Mohr-Coulomb plastic yield criterion given by:

$$\tau_y^i = min\left(\tau_{y,1}, \tau_{y,2}\right) = min\left(c_1 + \sigma^i\ tan\phi_1, c_2 + \sigma^i\ tan\phi_2\right) \tag{7}$$

where $\tau_{y,1}$ and $\tau_{y,2}$ are the shear strengths of the two materials in contact. The interface shear strength is related to the normal stress in the interface element σ^i. The above strength expression can lead to a bilinear plastic criterion for the interface in the (σ^i,τ_y^i) plane in case of cohesive materials (Zhang et al. 2008). Nevertheless, all the materials in the modelling are non-cohesive (Table 1) which implies a linear plastic criterion dictated by the plastic properties of the weaker material in contact. The values of the plastic parameters for the interfaces are: $c^i = 0\ MPa$, $\phi^i = 37°$, $\phi_c^i = 32°$, and $\psi^i = 5°$ for the core-filter interface (parameters of the core material); $c^i = 0\ MPa$, $\phi^i = 43°$, $\phi_c^i = 32°$, and $\psi^i = 11°$ for the two other interfaces (parameters of the transition material). The elastoplastic parameters of the interfaces are summarised in Table 2.

The simulated behaviours of the three interfaces along the height of the dam at the end of construction are detailed in Fig. 8. The results are presented in terms of total relative displacements (Δu_n^i,Δu_s^i) and stresses (σ^i,τ^i). The sign conventions are positive for interpenetration ($\Delta u_n^i > 0$) and compression ($\sigma^i > 0$) in the normal direction, as well as for clockwise rotation ($\Delta u_s^i > 0$) and shearing ($\tau^i > 0$) in the tangential direction. A clockwise shearing occurs when the side of the interface located towards the exterior of the dam slips in the downward direction.

The total relative displacements between the sides of the interfaces are illustrated in Fig. 8 (a). They corresponds to interpenetration and clockwise shearing. One can observe that the interpenetration remains limited with values lower than 1 cm in all interfaces. The maximal interpenetration is predicted at the bottom of the dam where the normal stress is the highest. The relative normal displacements remain similar along the height of the dam in the three interfaces.

It is to mention that the clockwise shearing is due to the differential settlements of the materials in contact and to their relatives movements at interfaces. Only the top part of the core-filter interface ($79 \leq y \leq 100\ m$) exhibits an anticlockwise shearing $\Delta u_s^i < 0$. Moreover, the relative shear displacements in the interfaces increase towards the exterior of the dam, with Δu_s^i in the transition-rockfill interface higher than in the others. It can also be observed that $\Delta u_s^i > \Delta u_n^i$ which is related to gravity effect (material dead weight) and to the relatively low value of K_s which allows tangential slipping at interface.

The normal and shear stresses in the interfaces are illustrated in Fig. 8 (b). Similar observations can be made about

Table 2. Elastoplastic interface parameters

Symbol	Name	Core-Filter	Filter-Transition	Transition-Rockfill	Unit
K_n	Normal stiffness	100	100	100	MPa/m
K_s	Tangential stiffness	10	10	10	MPa/m
c^i	Cohesion	0	0	0	MPa
ϕ^i	Friction angle	37	43	43	$^\circ$
ϕ_c^i	Critical (residual) friction angle	32	32	32	$^\circ$
ψ^i	Dilatancy angle	5	11	11	$^\circ$

the interfaces: in compression, under clockwise shearing unless at the top of the dam in the core-filter interface, τ^i increases towards the exterior of the dam, and σ^i is similar in the interfaces unless at the bottom of the dam. Nonetheless, $\tau^i < \sigma^i$ even if $\Delta u_s^i > \Delta u_n^i$ because $K_s < K_n$.

In the simulated behaviour of interfaces, the stiffness moduli are constant. A non-constant K_n evolving with the interface interpenetration would engender a reduction of interpenetration for the same normal stress level. However, the simulated interpenetration along all interfaces remains low. Thus, using a non-constant K_n to reduce the interpenetration is not necessary. A non-constant K_s evolving with the interface normal stress would restrain the tangential displacements between the materials in the lower part of the dam.

Nonetheless, field measurements during the dam constructions are necessary to quantify the large-scale interface behaviour, as its tangential displacement and possible slipping. Unfortunately, measurements inside the dams at material contacts are not easy to perform, thus not readily available at large scale.

Sensitivity analyses

The results detailed in Fig. 8 concern only the behaviour of the interfaces. Their effects on the dam overall behaviour are investigated hereafter in parametric studies. In fact, the dam overall behaviour depends on the interface's characteristics (K_n, K_s, and ϕ^i for non-cohesive materials) which are analysed independently.

Firstly, the sensitivity of interface and dam behaviours to the variation of the interface normal stiffness modulus is analysed. A variation of K_n between 10 and 1000 MPa/m is considered while keeping the other interface's parameters constant (Table 2). The influence on the interface behaviour is depicted in Fig. 9 for the filter-transition interface only. The influence on the other interfaces is similar. It is expected that K_n has mainly an influence in the normal direction (on Δu_n^i and σ^i) which is highlighted by the numerical results.

The relative displacements in Fig. 9 (a) indicate that the interface interpenetration Δu_n^i increases tremendously for low values of K_n. This increase is amplified from the top to the bottom of the dam for increasing normal stress in the interface. A maximal interpenetration value of $\Delta u_{n,max}^i = 5.5\ cm$ is observed for $K_n = 10\ MPa/m$ close to the bottom of the dam. This seems large for a contact between filter (sand or gravely sand) and transition (sandy gravel) materials. Thus, low values of K_n have to be avoided.

An increase of K_n leads to a decrease of the interpenetration almost towards a close contact without interpenetration $\Delta u_n^i \to 0$. Values of $K_n > 1000\ MPa/m$ lead to the opening of the interface with a loss of contact between the materials. This engenders a tremendous increase of the relative tangential displacement ($\Delta u_n^i < 0$, $\sigma^i = \tau^i = 0$, and $\Delta u_s^i >> 0$). The latter are not realistic in real embankment dams and want to be avoided. In fact, as aforementioned, the interfaces in embankment dams generally behave as closed contact (Tanchev 2014). Furthermore, while the interface interpenetration decreases (Fig. 9 (a)), the normal stress increases in the interface (Fig. 9 (b)) with the increase of K_n. Above a certain value of normal stiffness, σ^i stabilises and Δu_n^i keeps decreasing.

The influence of K_n variation on the dam overall behaviour is detailed in Fig. 10 along the horizontal cross-section at mid-height of the dam. It is compared to the reference case of direct glued contact. The results indicate that the variation of K_n does not have a significant influence on settlements and equivalent deviatoric strains. The only noticeable variation is on the settlements in the vicinity of the interfaces (Fig. 10 (a)).

Secondly, the sensitivity of interface and dam behaviours to the variation of the interface tangential stiffness modulus is studied. A variation of K_s between 1 and 100 MPa/m is considered while keeping the other interface's parameters constant (Table 2). The influence on the interface behaviour is illustrated in Fig. 11 for the filter-transition interface. It is expected that K_s has mainly an influence in the tangential direction on Δu_s^i and τ^i.

The results indicate that Δu_s^i decreases significantly with the increase of K_s and increases tremendously for a low value of $K_s = 1\ MPa/m$. For the latter, a maximal value of $\Delta u_{s,max}^i = 12.7\ cm$ is observed at $y = 20\ m$. However, this low value of tangential stiffness leads to the opening of

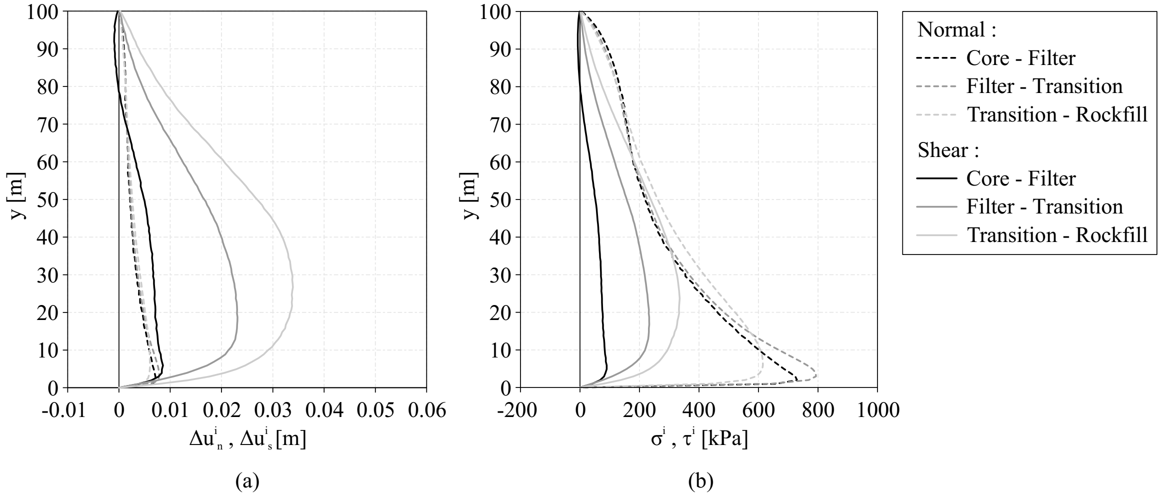


Figure 8. Interface behaviours for zero-thickness interface elements: (a) relative displacements and (b) stresses.

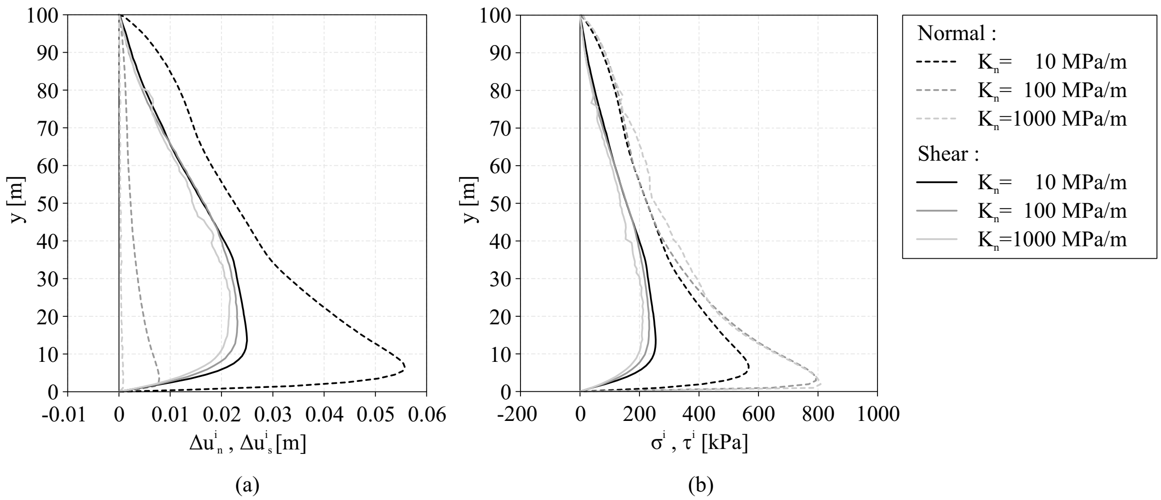


Figure 9. Influence of K_n on the filter-transition interface behaviour: (a) relative displacements and (b) stresses.

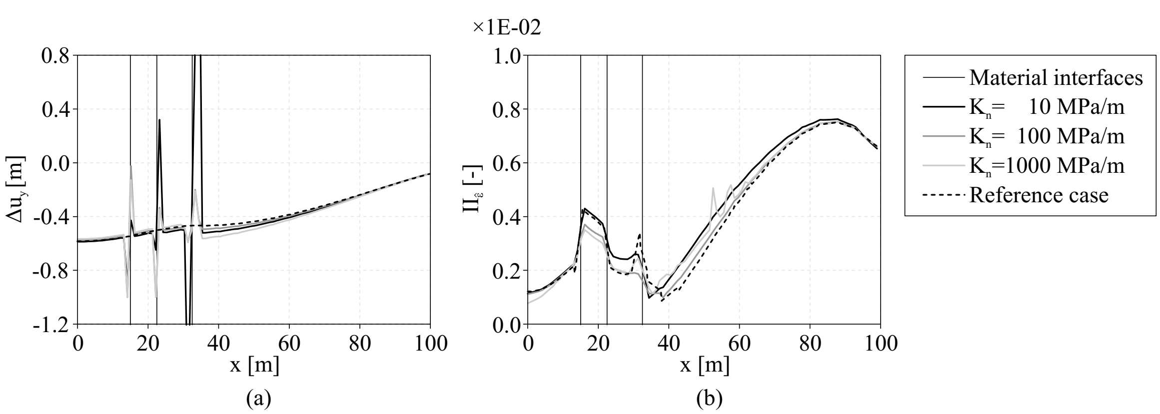


Figure 10. Influence of K_n on the dam behaviour: (a) settlements and (b) equivalent deviatoric strains along a horizontal cross-section at mid-height.

interface elements $\Delta u_n^i < 0$ for $10 \leq y \leq 40$ m. The low shear stiffness leads to large plastic shear strain at interface which engenders plastic dilatancy and interface opening. The opening occurs, not along the entire length of the material interface, but on some interface elements. The displayed results are average values over both sides of the interface elements. This leads to a rather irregular distribution of the local stresses in Fig. 11 (b). It is the appearance of interface opening which causes the important slipping at interface; therefore, the results for $K_s = 1$ MPa/m are not realistic. As for high values of K_n, low values of K_s for dilatant interfaces can also cause interface opening which want to be avoided by choosing adequate values of stiffness moduli.

The influence of K_s on the dam overall behaviour is detailed along the mid-height horizontal cross-section in Fig. 12. When compared to the reference case without interface elements, an increase of settlements and equivalent deviatoric strains is observed for decreasing values of shear stiffness. A transition of the dam overall behaviour appears clearly for the lower value of $K_s = 1$ MPa/m. Once again, this is related to the behaviour of the interfaces and to the loss of contact appearing in them. The loss of contact appears in the filter-transition interface but also in the transition-rockfill interface. This explains the transition of behaviour appearing especially in the rockfill. The increases of simulated settlements and shearing correspond to a downwards slipping of the rockfill along the contact with the transition material.

Finally, the sensitivity of interface and dam behaviours to the variation of the interface shear strength is analysed. Increasing the shear strength prevents plastic slipping at interfaces and produces identical results than for a glued condition. Thus, only the reduction of the shear strength in the interfaces is presented. As for the thin interface layers, an evolution of the material shear strength at interfaces towards residual values (critical state) is simulated in all the interfaces: $\phi^i = \phi_c^i = 32°$ and $\psi^i = 0°$ by Eq. 2. A second reduction of interface shear strength is realised by considering lower friction angles with $\phi^i = \phi_c^i = 10°$ and $\psi^i = 0°$. Both manners of reducing the interface shear strength simulate non-dilatant interfaces. The interface stiffness moduli $K_n = 100$ MPa/m and $K_s = 10$ MPa/m are kept constant (Table 2).

The influence on the interface behaviour is illustrated in Fig. 13 for the filter-transition interface. The reduction of the interface friction angle to its critical value $\phi^i = \phi_c^i = 32°$ does not modify the interface behaviour significantly. An important increase of Δu_s^i is observed for the lowest values of $\phi^i = \phi_c^i = 10°$ and corresponds to an important plastic slipping at interface (Fig. 13 (a)). A maximal value of $\Delta u_{s,max}^i = 7.7$ cm at $y = 20$ m is observed. An important increase of plastic slipping is also observed in the other interfaces especially in the transition-rockfill interface with $\Delta u_{s,max}^i = 62$ cm at $y = 37$ m. The stresses are also modified along the interface for $\phi^i = \phi_c^i = 10°$ (Fig. 13 (b)).

Comparing Fig. 13 to Fig. 11 indicates that reducing ϕ^i and K_s leads to similar effects on interfaces because they both condition their shear behaviour. The influence of ϕ^i reduction on the dam overall behaviour along the horizontal cross-section is not depicted because it leads to similar results than for the K_s reduction (Fig. 12). A transition of dam behaviour also appears for the lowest value of $\phi^i = 10°$. The influence on the settlements mainly occurs in the rockfill material. Nevertheless, the modelling of the dam construction for the low value of ϕ^i does not lead to interface opening because it involves an interface plastic behaviour without dilatancy.

DISCUSSION

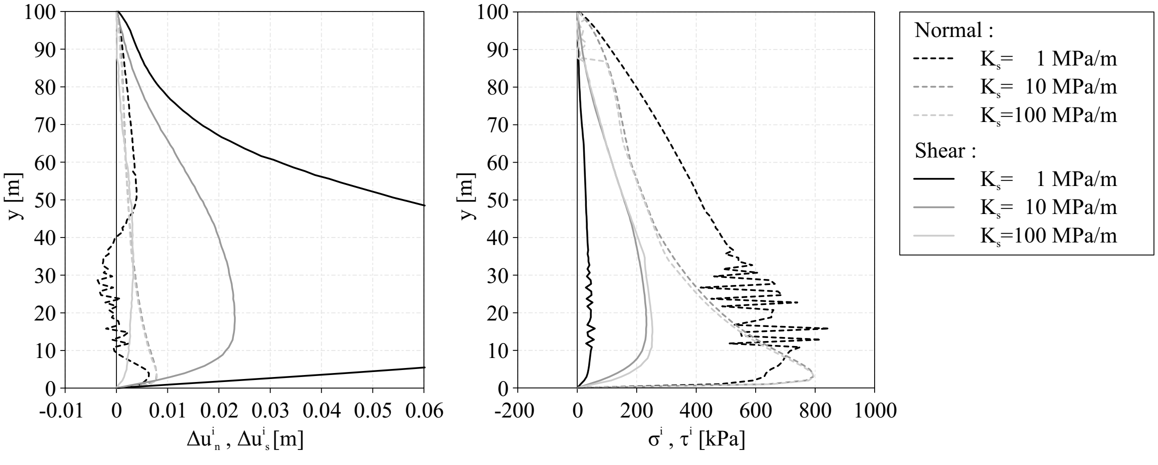
A discussion is presented to emphasise how the modelling of interfaces between granular materials composing zoned rockfill dams influences its behaviour, during the construction phase. Different types of interfaces and various characteristic values have been considered to highlight which properties affect the dam behaviour.

The influence of interfaces has been analysed for three types of interface modelling: glued interfaces with direct contact, glued interfaces with thin layers, and unglued interfaces with interface elements. For each interface type, sensitivity analyses have been performed on different resistance characteristics, either elastic or plastic. Their influences on the simulated behaviour of a dam has been mainly analysed on plasticity development, settlements, and shear deformations.

For glued direct contact, variations of the material elastic moduli impact the dam settlements and the development of plasticity in the different zones of the dam. Strong stiffness gradients between the materials can instigate differential settlements and interface shearing. Nevertheless, these effects remain limited because of the displacement compatibility. Variations of the material plastic shear strength has less impact on the dam behaviour. This is because the dam remains mostly in elastic state at the end of its construction.

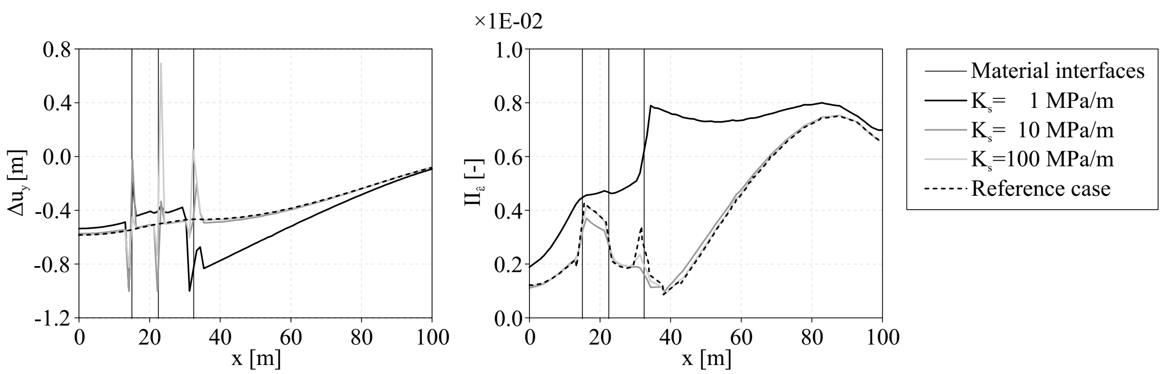
Still under glued condition, adding thin interface layers with average characteristics of the materials in contact does not affect the dam overall behaviour. It only reduces the plasticity development in the dam at the end of the construction. However, a resistance reduction (E^i or ϕ^i) of the thin layers has an important impact on the dam behaviour. It increases the deviatoric strains and the settlements in the dam whereas it does not affect the dam overall plasticity.

From the simulation results, it appears that the displacement compatibility at interfaces restricts the interface effects on the dam behaviour. The compatibility prevents relative displacements and tangential slipping. Thus, one must consider an unglued condition with the use of zero-thickness in-



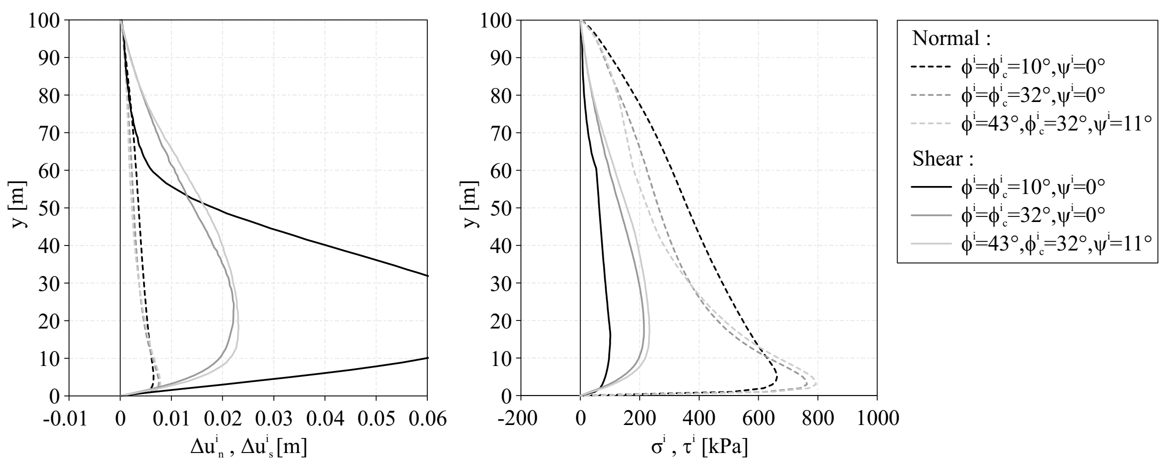
(a) (b)

Figure 11. Influence of K_s on the filter-transition interface behaviour: (a) relative displacements and (b) stresses.



(a) (b)

Figure 12. Influence of K_s on the dam behaviour: (a) settlements and (b) equivalent deviatoric strains along a horizontal cross-section at mid-height.



(a) (b)

Figure 13. Influence of ϕ^i and ψ^i on the filter-transition interface behaviour: (a) relative displacements and (b) stresses.

terface elements. With this approach, considering that the strength of a granular interface is dictated by the less resistant material in contact (Hu et al. 2010; Zhang et al. 2008) does not modify significantly the dam behaviour. Yet, simulating a reduction of interface resistance influences the dam behaviour. The variations of stiffness and shear strength can increase tremendously the interface relative displacements.

Nevertheless, interface opening, important interpenetration, and important tangential slipping are not realistic in embankment dams. They can be avoided by an adequate choice of the interface stiffness moduli. Too large or too low values of K_n have to be avoided to prevent interface opening and large interface interpenetration, respectively. For K_s, low values have to be avoided to prevent large interface slipping. Adequate values of stiffness have been discussed in the analyses of the simulation results, with regard to the relative displacements. More precise values can be estimated from acceptable relative displacements under a certain level of stress by $K_n = \sigma^i/\Delta u_n^i$ and $K_s = \tau^i/\Delta u_s^i$. Such evaluation depends on the nature of the materials in contact and would require experimental investigations.

Furthermore, the simulation of low shear resistance of interfaces induces interface slipping and a clear transition of the dam overall behaviour. The reductions of K_s and ϕ^i engender important settlements and shearing, especially in the rockfill. The simulations predict that these effects can be related to interface opening for K_s reduction.

The dilative behaviour of the interfaces under plastic shearing also affects the dam behaviour. In fact, the dilatancy causes interface opening (for low values of K_s) which in turn amplifies the interface slipping. The absence of interface dilatancy ($\psi^i = 0$) reduces the relative normal displacement of the interfaces. Furthermore, the dilative behaviour of granular interfaces is an ongoing topic of research for which only few analyses have been conducted. Hu et al. (2010) have observed experimentally that the dilatancy of granular soil interfaces is principally observed at pre-failure stage before interface rupture. Zhang et al. (2008) have also observed that a transition from dilative to contractive interface behaviour is observed when the confining stress is increased.

CONCLUSIONS

The influence of granular interfaces on the simulated mechanical behaviour of a rockfill dam during its construction has been analysed. The numerical results highlight that the contact condition between the granular materials as well as the interface elastoplastic characteristics influence the overall behaviour of the dam.

For glued contact, the variations of material elastic moduli, interface stiffness, and interface shear strength influence the dam behaviour. However, the influence remains restricted because of the displacement compatibility imposed at the interfaces. When relative displacements are allowed for unglued contact, the interface resistance has a strong influence on the dam. The reductions of stiffness and shear strength of interfaces increase tremendously the interface relative displacements and the dam settlement. A low interface shear resistance engenders a transition of the dam behaviour related to important interface slipping. The latter induces large settlements and large shearing in the dam, mainly in the external rockfill.

The dilative behaviour of the interfaces also affects the simulated behaviour of the dam. In fact, dilatancy induces interface opening and amplify the interface slipping. However, opening, important interpenetration, and important tangential slipping at the granular material interfaces are not realistic in embankment dams. Such relative displacements at the interfaces are avoided in the numerical simulations for adequate values of interface characteristics.

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NOTATIONS

Subscript $_0$	Initial quantities
Subscript $_c$	Critical (residual) quantities
Subscript $_n$	Quantities in the normal direction to interface
Subscript $_s$	Quantities in the tangential direction to interface
Subscript $_{max}$	Maximal quantities
Superscript ^{e}	Elastic quantities
Superscript ^{i}	Interface quantities
Dot notation $\dot{a}$	Time derivative (rate) of quantity a
γ_d	Dry weight density
ε_{ij}	Total strain tensor
$\hat{\varepsilon}_{ij}$	Deviatoric part of the total strain tensor
$II_{\hat{\varepsilon}}$	Second invariant of the deviatoric strain tensor
ν	Poisson's ratio
σ	Normal stress
σ^i	Normal stress in interface
σ_{ij}	Stress tensor
τ^i	Shear stress in interface
τ_y	Shear (yield) strength
τ_y^i	Shear (yield) strength of interface
ϕ	Friction angle
ϕ^i	Friction angle of interface
ψ	Dilatancy angle
ψ^i	Dilatancy angle of interface
c	Cohesion

c^i	Cohesion of interface
E	Young's elastic modulus
E^i	Young's elastic modulus of interface
K_n	Normal stiffness of interface
K_s	Tangential stiffness of interface
Δu_n^i	Relative normal displacement of interface (interpenetration)
Δu_s^i	Relative tangential displacement of interface
$\Delta u_s^{i,p}$	Interface plastic relative tangential displacement (interface slipping)
Δu_x	Horizontal displacement
Δu_y	Vertical displacement (settlement)
$\|\|\Delta u\|\|$	Displacement norm

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