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Interface porosity and the Dirichlet/Neumann pore fluid pressure boundary conditions in poroelasticity

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Abstract In this note we examine, through idealized computational modelling, the influences of the interface porosity in the contact between a free-draining non-deformable porous region and a poroelastic medium, as it relates to the specification of the Dirichlet/Neumann boundary conditions applicable to a porous interface.

Keywords Poroelasticity · Dirichlet/Neumann pore pressure boundary condition · Interface porosity · Finite element modelling

1 Introduction

The classical theory of poroelasticity proposed by Biot (1941) occupies an important position in the engineering sciences. The mathematical foundations of Biot's theory are well-documented in the literature in geomechanics and applied mechanics and it represents one of the most successful theories in classical continuum mechanics, second only to the classical theory of elasticity (Selvadurai 1996, 2007a; Lewis and Schrefler 1998; Coussy 2000; Auriault et al. 2002). The conventional pore fluid pressure boundary condition at the interface between a poroelastic medium and a free-draining porous medium is the Dirichlet condition applicable to pore fluid pressure at that surface. No distinction is made with regard to the microstructure of the contacting regions. This assumption is consistent with the idealization of the poroelastic medium where the pore fluid and the porous solid can occupy the same position at any given time.

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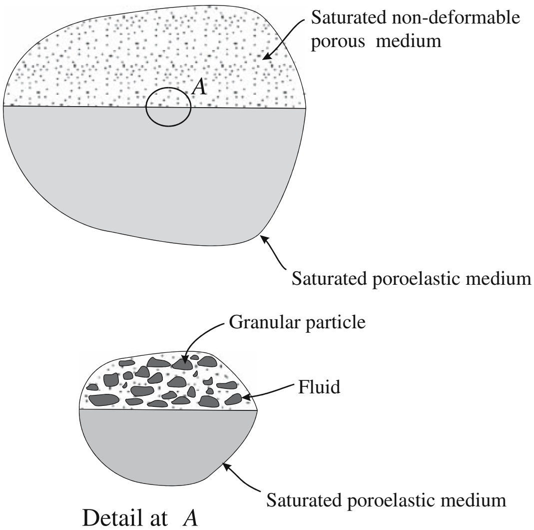

Fig. 1 The interface between a poroelastic medium and a free-draining porous boundary

When considering the microstructural features of the contact between the poroelastic medium and a free-draining porous medium, it is clear that pore fluid dissipation can occur only through the pore space of the boundary that allows the dissipation (Fig. 1). If the solid phase of the free-draining porous medium in contact with the poroelastic medium is impervious and this solid phase has a perfect contact, then the process of excess pore fluid pressure dissipation will be influenced by the reduction in the surface area available for its dissipation. This observation is not new. Quite early in the development of the theory of poroelasticity, Deresiewicz (1960, 1961, 1962) considered the effect of the interface condition on the propagation of Rayleigh-type surface waves in a poroelastic halfspace. These studies were extended by Deresiewicz and Skalak (1963) to consider uniqueness in dynamic poroelasticity, particularly in the presence of a dissimilar interface. Controversy has existed with regard to the correct forms of interface conditions that are necessary and sufficient for well-posedness of the interface condition (Cruz and Spanos 1989). In an informative and seminal paper, Gurevich and Schoenberg (1999) re-examined the issue of the interface conditions related to those posed by Deresiewicz and Skalak (1963) and they came to the conclusion that the limits of either *partially blocked* or *completely impermeable* interfaces can be resolved by considering the interface as a thin layer where the permeability is proportional to the layer thickness, as its thickness approaches zero. The issue of interface conditions at a porous interface also arises in classical fluid dynamics dealing with fluids that are bounded by permeable boundaries. Examples of such studies are given, among others, by Joseph and Tao (1964), Gheorghitza (1966), Beavers and Joseph (1967), Jones (1973), Saffman (1971) and Hsu et al.(2004).

This paper examines a three-dimensional problem in poroelasticity where Dirichlet boundary conditions are prescribed for the pore pressure on one part of the free-draining surface corresponding to the void region and either Dirichlet or Neumann pore pressure boundary conditions are prescribed respectively on the remainder of the surface that corresponds to either a free-draining or impervious solid region. A computational approach is used to examine the influence of the respective areas, which can be interpreted as an *area porosity* effect for the interface, on the overall degree of consolidation of the three-dimensional element.

2 Problem formulation

Ideally, when considering the contact between a free-draining but non-deformable porous medium and a poroelastic medium, it is necessary to consider a variety of contact conditions resulting from the penetration of the non-deformable porous medium into the poroelastic region. These can involve advancing contacts, receding contacts and other non-linear frictional constraints associated with the mechanics of contact between interfaces (Duvaut and Lions 1976; Selvadurai and Boulon 1995). The objective here is to adopt a much simpler version of an interface by representing it as a collection of rigidly interconnected impermeable/permeable disk-shaped contact regions, which are subjected to an external load. These disks are in contact with the poroelastic medium, thereby imposing either Dirichlet or Neumann conditions for the pore water pressure at the contact locations of the disks, and Dirichlet boundary conditions at the empty space between the disks. The disks can be arranged either in a square or a hexagonal pattern as shown in Figs. 2 and 3. The arrangement of these disks allows for the consideration of a variety of area porosity conditions at the interface, simply by altering the dimensions of the disks in relation to their spacing. The disks, which can be considered as the analogue of the solid grains of the free-draining porous medium, are considered to be either fully pervious or impervious. The latter boundary condition is the more realistic representation applicable to situations where the grains in contact with the poroelastic medium are impervious. For the purposes of illustration, however, the computational treatment will also examine the

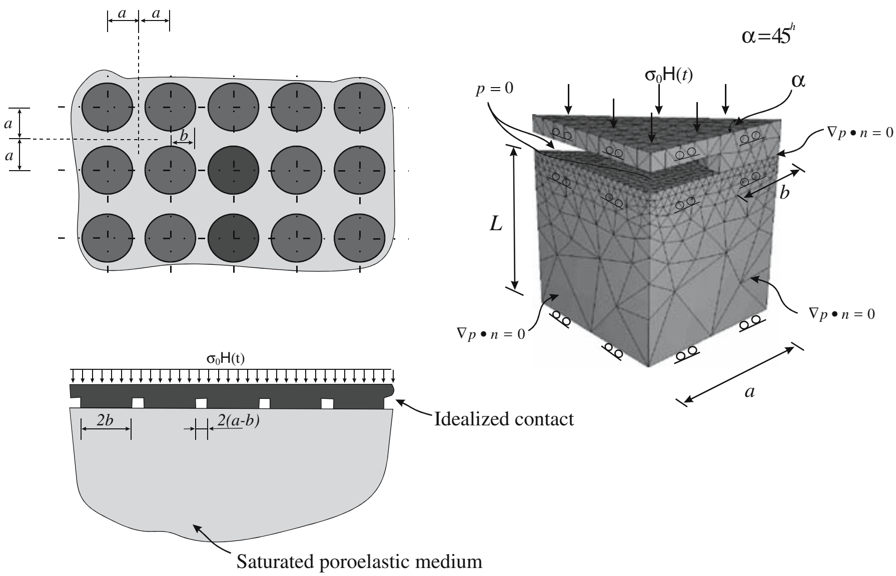

Fig. 2 The modelling of the contact between the poroelastic medium and the free-draining porous boundary: *Square* arrangement of contacting disks

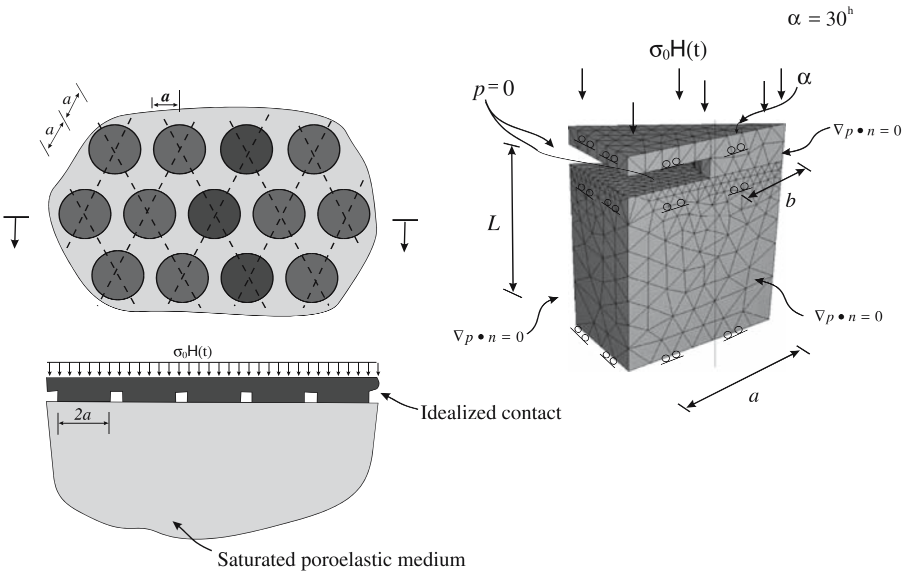

Fig. 3 The modelling of the contact between the poroelastic medium and the free draining porous boundary: *Hexagonal* arrangement of contacting disks

case where the contacting disk itself is assumed to be a rigid but completely porous region. The contact between the assembly of rigid interconnected disks and the poroelastic medium is achieved by the application of an external stress in the form of a Heaviside step function of time. The problem is effectively reduced to the consideration of a representative sector of the poroelastic medium and the free-draining porous interface, which is idealized by a segment of a disk. We consider a poroelastic layer of thickness L, which is in contact with an idealized interface consisting of a set of identical rigid disk-shaped elements of radius b that are arranged either in a square or a hexagonal planform. In view of the symmetries associated with the configuration of the rigid indentors, the uniform loading and the boundary conditions applicable to the drainage conditions, we can examine the consolidation response of the layer by restricting attention to representative elements as shown in Figs. 2 and 3 where appropriate displacement and pore fluid pressure boundary conditions are prescribed at the planes of symmetry. The rigid plate through which contact is established between the poroelastic medium and the pervious or impervious disks is also constrained to establish one-dimensional overall deformations of the medium.

For completeness, the initial boundary value problems that will be modelled using a conventional Galerkin finite element approach for the solution of the resulting poroelasticity problem are described. We consider the problem of a poroelastic medium consisting of an elastic porous skeleton that is saturated with a compressible pore fluid. The displacement field $\mathbf{u}(\mathbf{x}, t)$ and the pore fluid pressure $p(\mathbf{x}, t)$ are taken as the dependent variables, and $\mathbf{x}$ and t are the position vector and time, respectively. The partial differential equations governing these dependent variables are

$$\mu \nabla^2 \mathbf{u} + \frac{\mu}{(1-2\nu)} \nabla (\nabla \cdot \mathbf{u}) + \alpha \nabla p = \mathbf{0} \tag{1}$$

and

$$\frac{k\,\beta}{\gamma_{\mathrm{w}}}\nabla^2 p-\frac{\partial p}{\partial t}+\alpha\beta\frac{\partial}{\partial t}\left(\nabla\cdot\mathbf{u}\right)=0 \tag{2}$$

where

$$\beta=\frac{2\mu\,(1-2\nu)\,(1+\nu_{\mathrm{u}})^2}{9\,(\nu_{\mathrm{u}}-\nu)\,(1-2\nu_{\mathrm{u}})};\quad \alpha=\frac{3\,(\nu_{\mathrm{u}}-\nu)}{B\,(1-2\nu)\,(1+\nu_{\mathrm{u}})} \tag{3}$$

In Eqs. (1)–(3) μ and ν are respectively the linear elastic shear modulus and Poisson's ratio for the deformable skeleton of the poroelastic medium; ν_{u} is the undrained elastic shear modulus; k is the hydraulic conductivity of the porous medium; γ_{w} is the unit weight of water and B is Skempton's pore pressure parameter. We consider the uniform indentation of the surface S^* of the poroelastic halfspace by an array of rigid disks of equal radius that are symmetrically arranged in either a square or a hexagonal configuration (Figs. 2, 3). The radius of a circular disk is kept arbitrary, so that the contact area can be considered a variable. The disks are connected to a rigid plate that is subjected to a constant load in the form of a Heaviside step function of time, $\sigma_0\mathrm{H}(t)$. In view of the symmetry associated with the array of indenting circular disks, we can restrict the computational modelling to the solution of a sub-domain of the poroelastic layer where appropriate *displacement*, *effective traction* and *pore pressure* boundary conditions are applied on the planes of symmetry. The region of contact between the surface of the poroelastic layer and the circular rigid disk is denoted by S_{D} and the surface region exterior to the domain S_{D} is denoted by S_{E}. The surface $S=S_{\mathrm{D}}\cup S_{\mathrm{E}}$. Since the rigid disks enforce stationary contact, $S_{\mathrm{D}}\cap S_{\mathrm{E}}\equiv 0$. For the solution of the initial boundary value problem for the indented sub-domain, we consider the following two types of boundary conditions at the surface of the poroelastic medium.

For the completely porous smooth indenting rigid disk regions

$$u_z(x,y,0,t)=U(t);\quad (x,y)\in S_{\mathrm{D}};\quad t>0 \tag{4}$$

$$\sigma'_{xz}(x,y,0,t)=\sigma'_{yz}(x,y,0,t)=0;\qquad (x,y)\in S;\quad t>0 \tag{5}$$

$$\sigma'_{zz}(x,y,0,t)=0;\qquad (x,y)\in S_{\mathrm{E}};\quad t>0 \tag{6}$$

$$p(x,y,0,t)=0;\qquad (x,y)\in S;\quad t>0 \tag{7}$$

where $\boldsymbol{\sigma}'(\mathbf{x},t)$ is the stress tensor for the porous skeleton and $U(t)$ is an unknown constant displacement in the indenting region, which can be determined from the equilibrium condition for the disk region expressed in terms of the total stress tensor $\boldsymbol{\sigma}(\mathbf{x},t)$: i.e.

$$\int\!\!\int_S \sigma_0\,\mathrm{H}(t)\,\mathrm{d}S=\iint_{S_{\mathrm{D}}}\sigma_{zz}\,(x,y,0,t)\,\mathrm{d}S \tag{8}$$

The stress–strain relationship applicable to the poroelastic medium is given by

$$\boldsymbol{\sigma}=\boldsymbol{\sigma}'+\alpha\,p\,\mathbf{I}=\mu(\nabla\mathbf{u}+\mathbf{u}\nabla)+\frac{2\mu\nu}{(1-2\nu)}(\nabla\cdot\mathbf{u})\,\mathbf{I}+\alpha\,p\,\mathbf{I} \tag{9}$$

To complete the formulation of the initial boundary value problem we assume that prior to the application of the external loads, the porous skeleton and the pore fluid are unstressed: i.e.

$$\mathbf{u}(\mathbf{x}, 0) = 0; \quad p(\mathbf{x}, 0) = 0 \tag{10}$$

For the completely impervious adhering indenting rigid disk regions

$$u_z(x, y, 0, t) = U(t); \quad (x, y) \in S_{\mathrm{D}}; \quad t > 0 \tag{11}$$

$$u_x(x, y, 0, t) = u_y(x, y, 0, t) = 0; \quad (x, y) \in S_{\mathrm{D}}; \quad t > 0 \tag{12}$$

$$\sigma'_{zz}(x, y, 0, t) = \sigma'_{xz}(x, y, 0, t) = \sigma'_{yz}(x, y, 0, t) = 0; \quad (x, y) \in S_{\mathrm{E}}; \quad t > 0 \tag{13}$$

$$\left[\frac{\partial p}{\partial z}\right]_{z=0} = 0; \quad (x, y) \in S_{\mathrm{D}}; \quad t > 0 \tag{14}$$

$$p(x, y, 0, t) = 0; \quad (x, y) \in S_{\mathrm{E}}; \quad t > 0 \tag{15}$$

The unknown displacement $U(t)$ is obtained from the equilibrium condition (8).

3 Computational modelling and results

The initial boundary value problems that result from these particular idealizations of the poroelastic medium–porous medium interface are difficult to examine using analytical approaches (Selvadurai 2007a). Some progress can be made by restricting attention to the axisymmetric indentation of a circular column of a poroelastic material by a rigid disk indentor of smaller radius (Selvadurai 2007b); this solution however has limitations in capturing the complete geometry of the indented surface, which is important to the present modelling exercise. An equivalence in the surface areas can be imposed to generate an approximate result; this result, however, is not refined enough for examining accurately the relative influences of the permeable and impervious surface areas. For this reason, the poroelasticity problems associated with the porous interface are examined using a computational approach. Any standard computational code that has capabilities for solving poroelasticity problems and which maintains stability of the time-integration scheme and the correct order of the basis functions for the displacements and the pore fluid pressures can be used to obtain the desired numerical results. Details of the finite element approach for the study of poroelasticity problems are given in a number of standard texts (Lewis and Schrefler 1998) in computational methods and poromechanics and will not be described here. Also, no attempt is made to incorporate singularity elements to capture the various singularities in the contact stresses and pore pressure boundary conditions, which will be introduced as a result of the rigid nature of the indenting region (Selvadurai 2007a). Since the overall influence of the idealized porous interface is examined in relation to the overall displacements of the contacting region, the computational modelling is performed using conventional tetrahedral elements. The general purpose ABAQUS finite element code is used in the computational modelling and the element discretizations are shown in Figs. 2 and 3. For the purposes of developing the computational results, the poroelastic parameters are assigned the following values:

$$E = 2\mu(1+\nu) = 10 \text{ MPa}; \quad \nu = 0.3; \quad B = 1; \quad \nu_{\text{u}} = \frac{1}{2};$$
$$\kappa = \frac{k}{\gamma_{\text{w}}} = 0.2 \text{ mm}^4\text{N}^{-1}\text{s}^{-1}$$

For the presentation of the results, we use a non-dimensional time factor defined by ct/a^2, where a is the dimension of the sub-region shown in Figs. 2 and 3 and

$$c = \frac{2(1-\nu)(1+\nu_{\text{u}})^2}{(\nu_{\text{u}}-\nu)(1-\nu_{\text{u}})}\mu\kappa B^2 = 2.222 \text{ mm}^2/\text{s}$$

Also the results of the modelling are examined in terms of the time-dependent variation in the non-dimensional degree of consolidation $\bar{U}(t)$ defined by $[U(t) - U(0)]/[U(\infty) - U(0)]$ as a function of the non-dimensional time factor ct/a^2. The choice of this representation of the results is appropriate since the rate of consolidation of the indented poroelastic layer is expected to be influenced by the area porosity of the contact, represented by $n_{\text{A}} = S_{\text{E}}/S$.

We first examine the problem of the indentation of a porous layer by a hexagonal arrangement of indenting disks. The height of the porous column is set equal to the dimension a, which represents a relatively thin poroelastic layer. Figure 4 illustrates the influence of the permeability boundary conditions *within the indenting region* on the degree of consolidation $\bar{U}(t)$. The area porosity of the interface $n_{\text{A}} \approx 0.7733$ and the indentor arrangement corresponds to the hexagonal configuration. In this case the influence of the drainage boundary condition on the consolidation response is marginal. Analogous results for the indentation involving the square arrangement of the circular indenting regions are given in Fig. 5, and again the influence of the permeability of the contacting region is marginal. We next consider the case of the indentation of a poroelastic layer with $L = a$, where the indenting circular regions are in contact with each other. This corresponds to an area porosity $n_{\text{A}} = 0.0931$, which represents a significant reduction in the area available for pore fluid drainage. Figures 6 and 7 illustrate the variation of $\bar{U}(t)$ with ct/a^2, for the disk contact arrangements corresponding to the hexagonal and square configurations, respectively. In this case both arrangements of the indentors illustrate an appreciable influence on the rate of consolidation $\bar{U}(t)$. As expected, the final consolidation response is uninfluenced by the area porosity. Computations were conducted to examine whether the differences observed in the rate of consolidation of the poroelastic layer were a result of the aspect ratio of the layer thickness in relation to the radius of the indenting rigid region. Figures 8 and 9 illustrate the consolidation response for the layer of thickness $L = 10a$, where the indentor geometries correspond to the hexagonal and square configurations, respectively. These results also take into consideration the influence of the pore pressure boundary conditions within the indenting region, corresponding to either fully draining or completely impervious cases. The computational results indicate that the consolidation response in the initial stages of the consolidation process is influenced by the area porosity of the contacting region. The impermeable indentation, which corresponds to the practical situation involving a free-draining boundary of low porosity, would tend to impede the fluid migration at the interface, thereby altering the effectiveness of the drainage and the time scales involved in achieving complete consolidation.

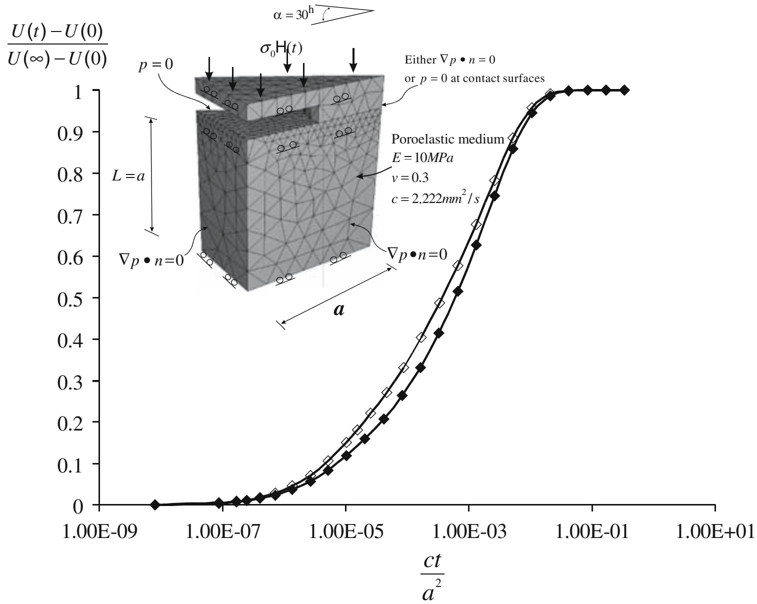

Fig. 4 Consolidation of a soil layer of finite thickness with a contact area porosity $n_{\mathrm{A}} = 0.7733$; hexagonal arrangement with $\alpha = 30°$ and geometry ratio $L = a$. [The solid symbols represent impermeable indentation, i.e. $\nabla p \cdot \mathbf{n} = 0$; unfilled symbols represent fully permeable indentation, i.e. $p = 0$]

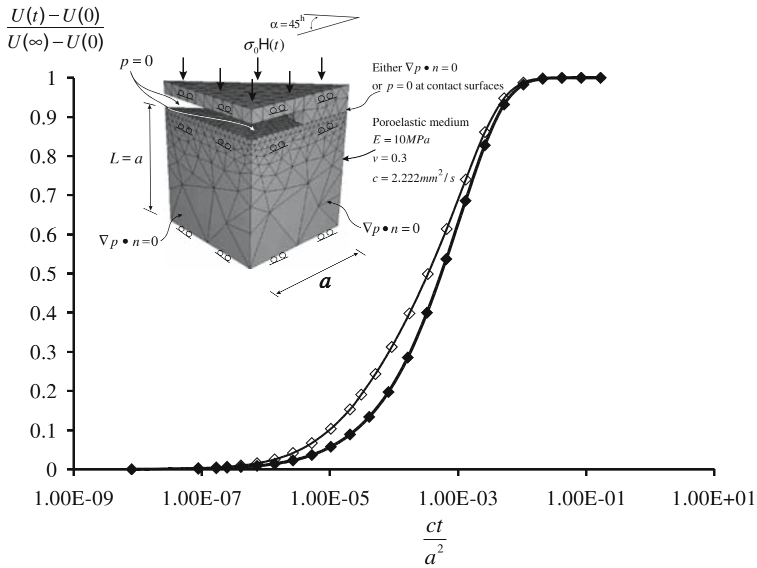

Fig. 5 Consolidation of a soil layer of finite thickness with a contact area porosity $n_{\mathrm{A}} = 0.7733$; square arrangement with $\alpha = 45°$ and geometry ratio $L = a$. [The solid symbols represent impermeable indentation, i.e. $\nabla p \cdot \mathbf{n} = 0$; unfilled symbols represent fully permeable indentation, i.e. $p = 0$]

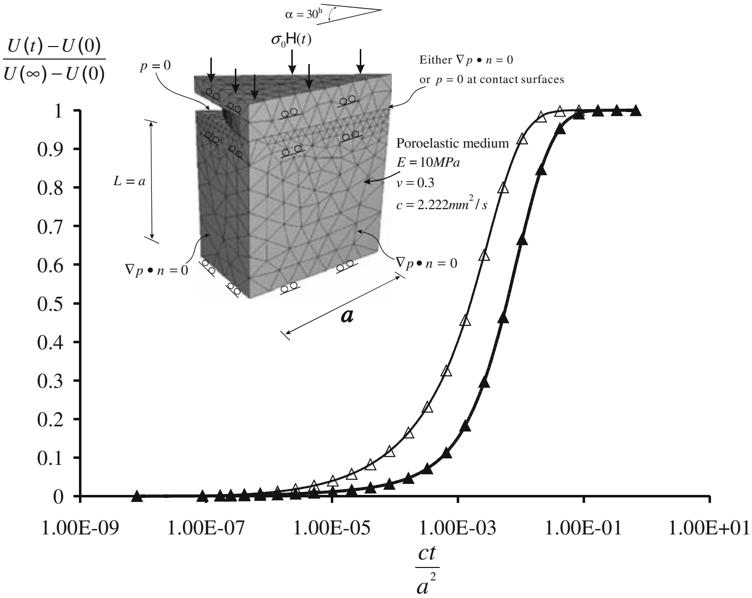

Fig. 6 Consolidation of a soil layer of finite thickness with a contact area porosity $n_A = 0.0931$; hexagonal arrangement with $\alpha = 30°$ and geometry ratio $L = a$. [The solid symbols represent impermeable indentation, i.e. $\nabla p \cdot \mathbf{n} = 0$; unfilled symbols represent fully permeable indentation, i.e. $p = 0$]

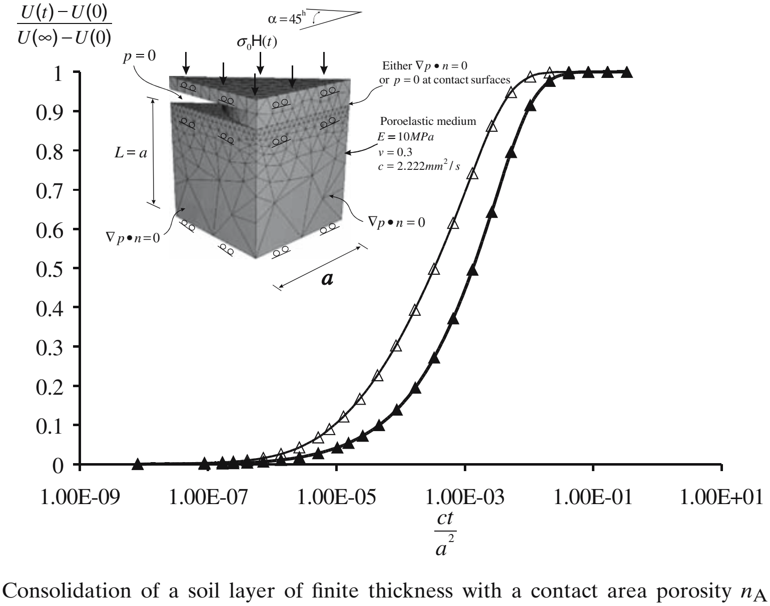

Fig. 7 Consolidation of a soil layer of finite thickness with a contact area porosity $n_A = 0.0931$; square arrangement with $\alpha = 45°$ and geometry ratio $L = a$. [The solid symbols represent impermeable indentation, i.e. $\nabla p \cdot \mathbf{n} = 0$; unfilled symbols represent fully permeable indentation, i.e. $p = 0$]

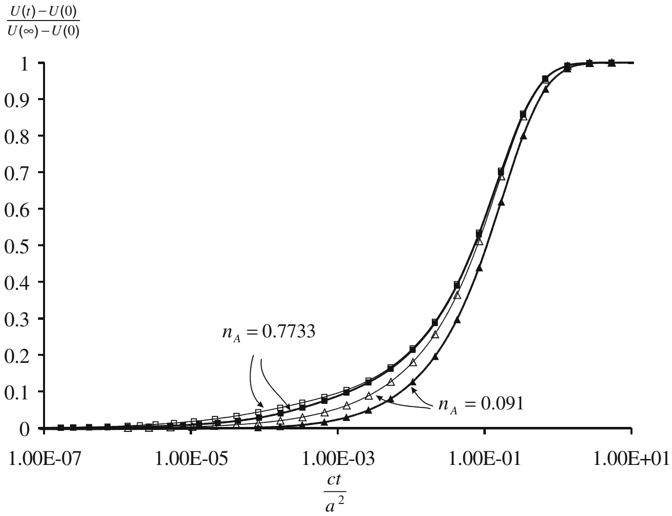

Fig. 8 Consolidation of a soil layer of finite thickness; hexagonal arrangement with $\alpha = 30°$ and geometry ratio $L = 10a$. [The solid symbols represent impermeable indentation, i.e. $\nabla p \cdot \mathbf{n} = 0$; unfilled symbols represent fully permeable indentation, i.e. $p = 0$]

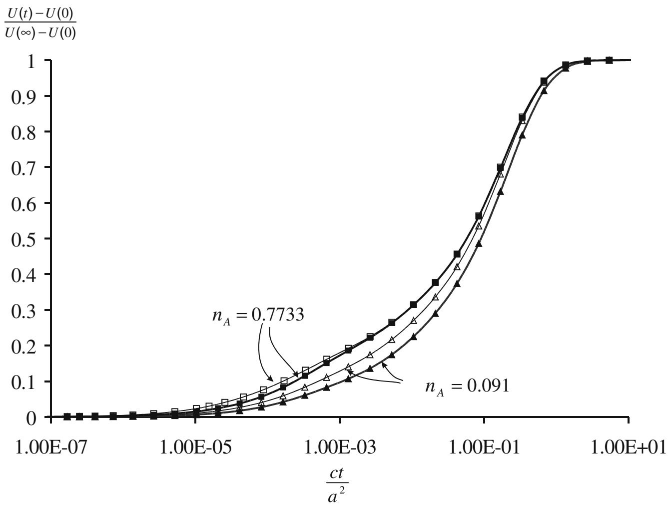

Fig. 9 Consolidation of a soil layer of finite thickness; hexagonal arrangement with $\alpha = 45°$ and geometry ratio $L = 10a$. [The solid symbols represent impermeable indentation, i.e. $\nabla p \cdot \mathbf{n} = 0$; unfilled symbols represent fully permeable indentation, i.e. $p = 0$]

4 Concluding remarks

This paper provides a relatively simple examination of the Dirichlet boundary condition that is associated with an interface between a poroelastic medium and a free-draining porous region. The contacting non-deformable porous medium is represented by an idealized array of rigid disks arranged in a regular fashion. These disks can be either be completely *free-draining* (Dirichlet boundary conditions for the pore fluid pressure at the contacting regions) or *completely impervious* (Neumann boundary conditions for the pore fluid pressure at the contacting regions). There is no consideration of variability of the size of the contacting regions or the possibility of the penetration of the contacting region into the poroelastic medium, which can give rise to moving boundary problems at the interface. The interface property of interest is the *area porosity* of the interface and the consolidation process is also influenced by the relative dimensions of the consolidating region in relation to a characteristic length of the particle scale of the free-draining porous medium. The objective of the study is to pose the question as it relates to the role of the *area porosity* of the interface in controlling the form of a pore fluid pressure boundary condition applicable to a consolidating poroelastic medium in contact with a porous medium. Admittedly, the porosity of a porous boundary consisting of impervious grains will exert an influence on the consolidation process, in as much as a porosity of unity will correspond to a strict Dirichlet-type boundary condition and a porosity of zero would correspond to a Neumann-type boundary condition. In most applications of poroelasticity in the geosciences, however, the porosities of the contacting regions for geologic materials would roughly correspond to the volume porosities of free-draining porous media. These porosities can range from 0.5% to 30% depending on the type of geomaterial (Farmer 1968). The results of this investigation suggest that for porosities in the range of ten percent the influence of the area porosity on the consolidation process can be appreciable, particularly in terms of an alteration in the time-scales associated with achieving the same degree of consolidation. In this sense, when the porosity of the contacting region is relatively low, a more accurate formulation of a boundary value problem in poroelasticity should also take into consideration the possible development of fluid pressure transients in the contacting porous medium itself. Such an interface can be described as a leaky interface that would account for both continuity of the pore fluid pressures and the mass flow rate between the poroelastic medium and the porous boundary. This study complements the findings of Gurevich and Schoenberg (1999), in the sense that in order to account for the extreme limits of the interface porosity, it is necessary to introduce an interface layer where there is a gradual transition in the permeability from that of the poroelastic medium to the porous region in contact with the poroelastic medium in a rational way. The approach suggested above is certainly a fruitful way of accommodating the extreme limits. In terms of computational modelling, it is also possible to use a non-deforming interface layer in which the permeability is adjusted to account for the reduced area available for fluid transfer by virtue of the impervious grains of the contacting non-deformable porous medium. This condition becomes relevant when the assessment of the rate of consolidation is of interest. It should also be noted that for quasi-static problems, the role of this interface porosity is to alter the *rate of consolidation* of the poroelastic medium and that the *final consolidation settlement* is, however, *uninfluenced* by the interface permeability.

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