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Numerical Modeling of Anisotropic Gravel Pack Behavior on Open-hole Completions

Mohara de Oliveira Nascimento
Student, Pontifical Catholic University of Rio de Janeiro, Rio de Janeiro, Brazil, mohara.civil@gmail.com

Eleazar Cristian Mejia Sanchez
Researcher, Tecgraf Institute, Rio de Janeiro, Brazil, crisms@tecgraf.puc-rio.br

Deane Roehl
Chief Researcher, Tecgraf Institute, Rio de Janeiro, Brazil, deane@tecgraf.puc-rio.br

ABSTRACT: Sand production is a worldwide phenomenon that impacts the service life of oil and gas wells, being present in intervals of poorly or unconsolidated rocks. When sand production occurs, some elements are included with the completion structures, intending to stop the produced solids from entering the well. One of them is gravel packing, which consists of a mechanical filter composed of a steel screen and a granular packing. Predicting the behavior and properties of this package is a challenge. Thus, this paper proposes an anisotropic constitutive model to describe the mechanical behavior of a granular package used in an open-hole gravel pack completion. The mechanical properties of the model are calibrated with the literature results of a polyaxial test on a synthetic sandstone cube. In the test, sample loading is divided into two steps. The first one is under confining stress up to a specific limit, and the second increases stress only in the vertical direction. The numerical model adopts a nonlinear elastic behavior in the gravel packing to simulate the effect of the compaction and the increase of particle contacts. Since the stress in the second phase is vertical, causing the arrangement of grains to be greater in one direction than in the other, the gravel packing is considered anisotropic. The study compares the induced displacements in each loading step with excellent agreement between the numerical and available experimental data. Finally, the proposed approach is an attractive alternative to predict the mechanical behavior of gravel packing with good accuracy.

KEYWORDS: Gravel pack, Open-hole completion, Anisotropic behavior, Finite element method.

1 INTRODUCTION

Many hydrocarbon reservoirs are in weak, poorly consolidated, or unconsolidated rocks, such as sandstones and chalk. These rocks generally present incomplete cementation and are susceptible to the desegregation of particles when the formation is subject to stresses high enough to cause its rupture, resulting in a process called solids or sand production. The main concern when rock undergoes sand production is the possibility of the particles produced entering the well along with the reservoir fluid during the hydrocarbon production. Given that these particles are abrasive and can cause the erosion of the well's equipment, in addition to the chance of plugging the tubes due to large amounts of solids (Fjaer et al., 2008).

To deal with this problem some techniques are applied, being separated into methods that are related to the consolidation of the rock, adding artificial consolidation (with resin injection), or opting for exploring only intervals of strong formations (with selective or oriented perforating), and methods that aim to avoid or control the solids production using structures such as slotted liners, sand screens, gravel packing, and frack packing. The great advantage of methods that apply mechanical components instead of consolidation techniques is their wide applicability, as they are not limited to short or high-strength intervals (Mahmud et al., 2020).

Among the structures mentioned, gravel packing is a wise method that combines an efficient granular medium with a sand screen. In the gravel pack system, the granular medium assumes a dual function: stabilize the borehole wall, in case of open-hole completions, and retain the produced particles, acting as a filter. At the same time, the sand screen is a perforated steel tube that has openings small enough to contain the gravel pack particles and large enough to allow the fluid production to pass through.

The use of the gravel packing as a sand control component can be done in both cased-hole and open-hole wells. In the first case, the elements act jointly with the typical completion structures (cement and casing), and in the second, they act alone in direct contact with the formation. The present paper focuses on the second case intending to find out the properties and understand the behavior of the granular material based on the results of an experimental test available in the literature. The adopted methodology was to model the experiment using the finite element method and calibrate the gravel properties according to the literature results.

Vargas et al. (2012) performed the reference experimental test and developed numerical studies with continuum and continuum-discrete models. Comparing these approaches the authors conclude that the continuum modeling shows a better fit to the experimental results. In the present paper, a numerical continuum model is also proposed, changing the properties and assumptions about the gravel, intending to produce an even better approximation. For that, extensive research was conducted, providing a comprehension of the movement and rearrangement of the gravel particles when the gravel pack is subject to different loads, and explaining the gravel anisotropic behavior (Chen et al., 2020; Oda, 1993; Hoque & Tatsuoka, 1998; Hicher & Chang, 2006). Therefore, the granular material of the gravel pack was simulated using a nonlinear elastic and anisotropic model, where Young's modulus changes according to the relation of vertical and horizontal stresses. Finally, the modeling results were compared to the experimental and numerical reference data, validating the calibration and bringing a useful understanding of the gravel pack behavior.

2 EXPERIMENTAL TEST

The reference experimental test, detailed in the works of Chavez (2011) and Vargas et al. (2012), consists of a polyaxial test on a synthetic sandstone cube with a centralized hole, which is partially filled with granular material confined by a screen. The test aimed to simulate an open-hole well with sand control structures, in a manner that the synthetic sandstone represents the formation, and the other components represent the gravel pack. Thus, Figure 1 shows: the polyaxial cell used in the experiment (Fig. 1a), the centralized hole with gravel pack (Fig. 1b), and the clip gages applied to measure the screen displacements (Fig. 1c). The dimensions of the experimental sample were: 30x30x30 cm for the sandstone cube, 6cm in diameter for the hole, and a thickness of 0.52mm and 3.8 cm in internal diameter for the screen.

(a) (b) (c)

Figure 1. Experimental setup: (a) Polyaxial cell, (b) gravel pack, and (c) clip gages (Vargas et al., 2012).

Table 1 shows the properties of the materials used in the synthetic sandstone cube and the sand screen; these values were obtained by the reference through tests. The granular material of the gravel pack was not tested, so its properties were unavailable.

Table 1. Mechanical properties of the materials (Vargas et al., 2012).

Material	Young's modulus (GPa)	Poisson's ratio	Yield stress (MPa)	Friction angle (º)	Cohesion (MPa)
Synthetic sandstone	2.70	0.27	-	28	5.50
Screen (Brass tube)	90.60	0.32	484	-	-

The experiment loading sequence was separated into two phases, according to Figure 2, in the first phase the cube was loaded in the directions perpendicular to the hole, with confining stress that initiates at 1.38 MPa and ends at 4.13 MPa; and in the second phase, deviatoric stress was applied in the vertical faces, with values of 4.83 MPa to 11.03 MPa. In both phases, the cube was loaded incrementally during 6 and 102 minutes, respectively. Along the test, the faces parallel to the hole were restricted, with no displacements allowed.

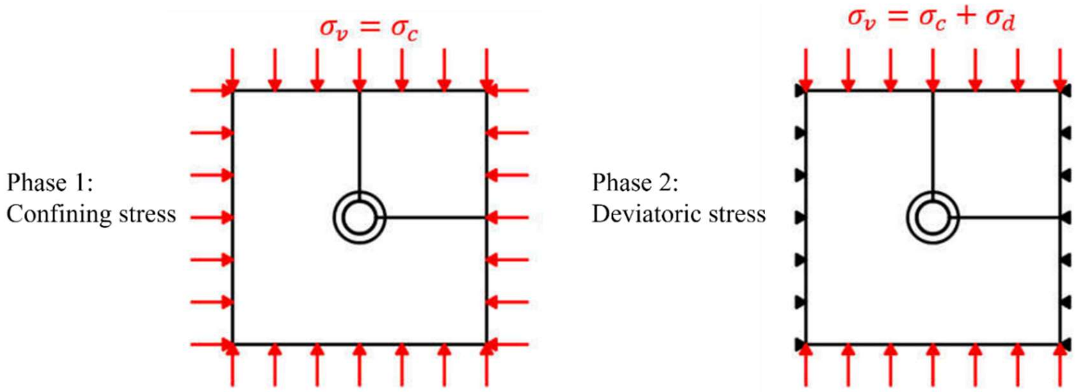


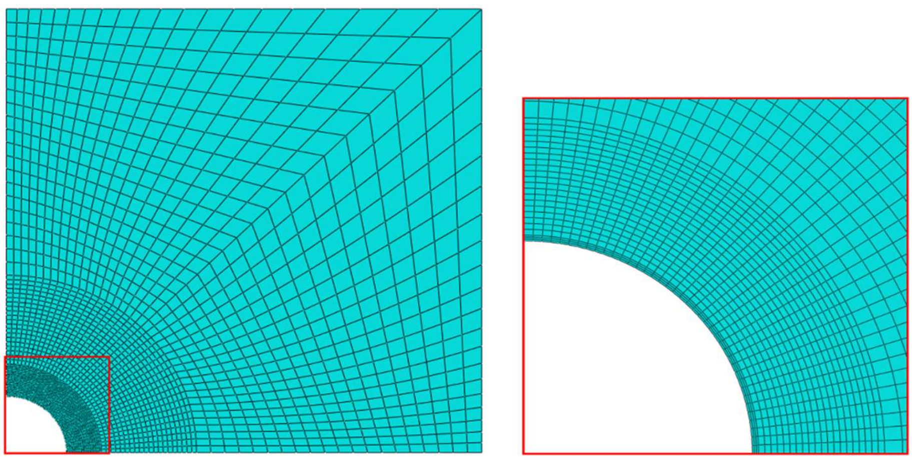
Figure 2. Experiment loading phases.

3 NUMERICAL MODELING

This section presents a proposed numerical model that simulates the experimental test described previously. The model developed here focuses on finding the properties of the granular material used in the gravel pack since this material was not tested and their properties are unknown. Hence, the characteristics of the model, the study behind the calibration of the gravel properties, and the comparative results are discussed next.

3.1 Geometry and finite element mesh

The numerical simulation has been carried out using the software ABAQUS, a potential tool used in reference works that also model wells subject to sand production (Santos et al., 2008; Hilbert et al., 2011; Xu et al., 2014). To validate the model and make a fair comparison with the numerical model developed by Vargas et al. (2012), the same type of finite element and a similar mesh were used. Thereby, the finite element chosen was the 4-node plane strain element (CPE4) and the structure was discretized in a mesh of 2520 elements and 2624 nodes, with 1600 elements for the formation, 800 elements for the gravel package, and 120 elements for the sand screen, as shown in Figure 3.



(a) (b)

Figure 3. Mesh discretization: (a) all model, (b) gravel pack.

Since the experiment was made in a cube cell with boundary conditions that allow symmetry in the horizontal and vertical axis, the model corresponds only to a ¼ of the cube geometry, being enough to capture the behavior of the structures.

3.2 Gravel pack properties

Defining the properties of the gravel pack was a challenge, since the literature shows different sets of values, as noted in Table 2. For that reason, some approaches were tested until finding the set of properties that was adopted in this paper. Initially, we developed models with fixed Young's modulus of 60, 100, 200, and 2000 MPa. However, none of them showed satisfactory results, with displacement curves far from the reference.

Table 2. Reference mechanical properties for the gravel pack.

Reference	Young's modulus (MPa)	Poisson's ratio	Friction angle (º)	Cohesion (MPa)
Xu et al. (2014)	100	0.35	30	20
Vargas et al. (2012)	0.9 - 200	0.34-0.35	32	0
Hicher & Chang (2006)	2000	0.21	-	-

Based on Vargas et al. (2012) we start to assume that the material is nonlinear with dependence on the applied stresses. Another considered assumption was that the granular material has stress-induced anisotropy with different Young's modulus in directions horizontal and vertical. This concept is defended by Hicher & Chang (2006) and Hoque & Tatsuoka (1998). These authors also explain that the most deposited granular materials exhibit cross-anisotropy, with a direct relation between Young's modulus and stresses, vertical and horizontal.

Hicher & Chang (2006) developed in their work curves that show the influence of the ratio of the stresses σ_v/σ_h and the ratio of the Young's modulus E_v/E_h expressing the stress-induced anisotropy for two types of granular materials (hime gravel and toyoura sand), we extend these curves for the material applied in the experiment, which is a ceramic proppant called Carbolite. With this, it was possible to calibrate the gravel pack and find the set of properties shown in Table 3.

Table 3. Calibrated mechanical properties of the gravel pack material.

σ_v/σ_h	E_v/E_h	E_v (MPa)	E_h (MPa)	v_{vh}
0	1.00	13	13	0.284
1.00	1.00	15	15	0.284
2.00	1.80	23	12.77	0.284
2.30	1.90	50	26.32	0.284
2.50	1.95	60	30.77	0.284
3.00	2.44	150	61.47	0.284
3.20	2.63	200	76.05	0.284
3.50	2.86	250	87.41	0.284
4.00	3.33	300	90.09	0.284
4.50	3.85	600	155.84	0.284
5.00	4.20	1000	238.09	0.284
6.00	4.54	2000	440	0.284

The values of Table 3 were inserted in Abaqus through a subroutine, intending to simulate the behavior of the gravel, considering the increase of Young's modulus in the direction where the stress is larger. A relevant fact to highlight is that while the σ_v/σ_h is equal to 1, the E_v is equal to E_h indicating that there is no stress-induced anisotropy at this point. The idea behind it is that in the confining phase, Young's modulus is the same in both directions, but in the deviatoric phase the E_v is larger than E_h, once the stress is applied only in the vertical direction, in a manner that the particles are more compacted and the stiffness in this region is larger.

These concepts can be visualized in Figure 4, which demonstrates how the subroutine works, with the compaction of the particles following the stress-induced anisotropy.

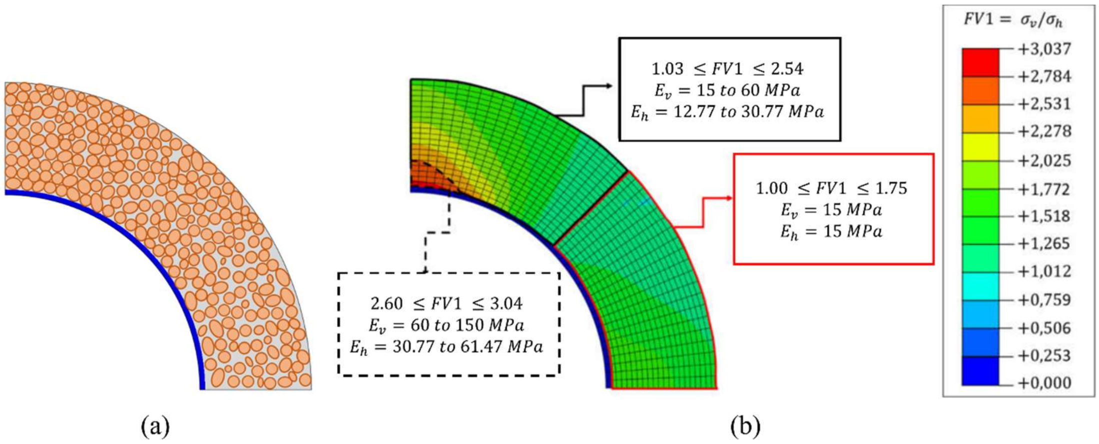


Figure 4. Arrangement of particles (a) and values of subroutine (b).

3.3 Results

In summary, the properties adopted in the proposed model were present in Table 1, for the sandstone and the sand screen, and in Table 3, for the calibrated gravel pack. The main difference between the model built here and the numerical model of Vargas et al. (2012) is that in this work we assume the material is anisotropic and the dependence of Young's modulus is related to the ratio of the stresses. Besides, we consider Young's vertical modulus initiating in 13 MPa and going to 2000 MPa, with a nonlinear anisotropic behavior. Finally, it was possible to validate the proposed model by comparing the results with the curves of the results of the experiment and the numerical model of Vargas et al. (2012).

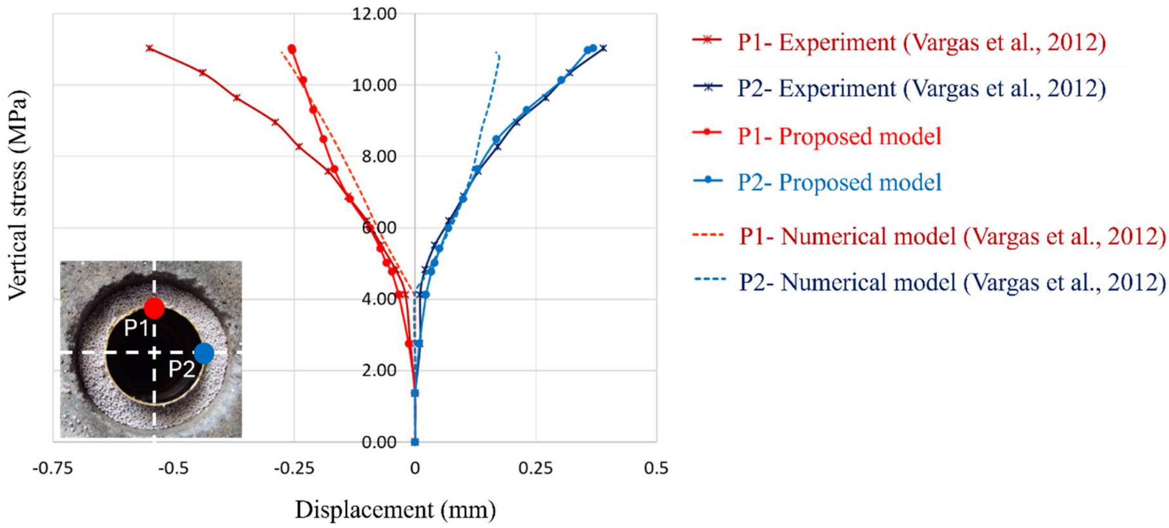


Figure 5. Comparative results.

Figure 5 shows the curves of displacement versus vertical stress in points P1 and P2 located inside the sand screen, measured by the clip gages visualized in Figure 1c. The results highlight the proposed model can fit satisfactorily the curves of displacements in the sand screen, indicating that the calibration of the gravel pack was successful, mainly for the point P2. Nonetheless, the curve of point P1 increases at a different rate compared to the experiment and must be more investigated.

4 CONCLUSIONS

This work has presented a new approach to modeling the granular material present in the gravel pack system, involving the consideration of a nonlinear anisotropic behavior. The main concern of this paper was to simulate adequately the natural rearrangement of the particles when the structure is loaded. For that reason, a subroutine was created, assuming the variable Young's modulus, which increases with the applied stresses. The results of this study were compared to a reference experimental test and a numerical model, both performed by Vargas et al. (2012), having a good fit with the experiment data and bringing a better response than the reference numerical model.

The hypotheses adopted here provide a useful methodology that can be applied in models with gravel pack structures, considering characteristics inherent to the granular material. For future work, extensions of this paper could be proposed, approximating more precisely the response of the system. Furthermore, it is interesting to adapt this model to other experimental tests, comparing the found parameters through a sensibility study.

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