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CFD-DEM Simulation of Multi-particle Arching at Sand Filter Opening

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***Abstract*—The primary motivation of this research is to offer an insight into the conditions and parameters that influence on the formation, stabilization, destruction and reformation of the multi-particle sand arching (bridging) as an efficient particle retention mechanism occurred at filter opening. The arching phenomenon is numerically explored by coupling two tools: CFD to model the fluid flow, and DEM to model the particle flow. The coupling is done in STAR-CCM+ (SIEMENS PLM). In this research, the arching at the filter opening at the micro-scale with heavy oil as the carrier phase of particles (in oil sand reservoirs) is investigated. The research outcome of this study is a computational fluid dynamic (CFD) - discrete element method (DEM) model cable of predicting multi-particle arch formation, stabilization, breakage and reformation. In particular, some of the parameters and conditions that could affect multi-particle arch performance are also studied such as size and shape of the particles and particle size distribution. Applying and advancing the knowledge gained in this research will help the research industry partner make better decisions about filter selection and filter opening design.**

***Index Terms*—Retention mechanisms, Multi-particle arching, Bridging, Plugging, Particulate flow modeling, CFD-DEM simulation**

I. INTRODUCTION

Sands destroy the oil production equipment, such as pipes and pumps [1]. Sand control technology reduces energy costs for oil and gas industry [2]. By using sand filtration [3], with the same amount of energy, more oil will be produced [2]. The multi-particle arching phenomenon [4] also known as bridging that is occurred at filter opening helps with sand retention [5] and is critical in sand filtration because a stable multi-particle arch supports sand filtration [6].

In this research, some of the conditions and parameters support the stability of the multi-particle sand arching are explored. Some conditions that may cause it to break [7], as well as the reformation after breakage will be investigated.

This research supports reduced sand production in oil wells and increased oil production while consuming the same amount of energy. The arching phenomenon helps with sand-retention and is critical in sand filtration because a stable sand arch supports sand filtration [8].

A. Plugging and Particle Build-up at Filter Opening

The filter open flow area, that is the area of filter open to flow, and mesh size or opening size of the filter are the factors considered when selecting a filter. Solid particle buildup and plugging [9], [10] at the entrance and throughout the length of the filter opening are the common failure [11] mechanisms in filters. Plugging is the reduction in the open flow area of the filter, mainly due to trapped solid particles. Plugging is an issue because it decreases the efficiency of filter. Particle buildup [12], another undesirable phenomenon, also happens due to the transport of very small particles in the system.

In some cases, solid particles can form bridges (arches) on the filter opening, which is known as bridging (arching) phenomenon. This bridging could be a hydrodynamic [13] phenomenon that happens due to flow convergence [14], or mechanical [15] due to the high concentration of the particles at the opening. The bridging phenomenon is important because it plays a key role in preventing plugging and stops the solid particles from passing through the filter.

B. Retention Mechanisms in Sand Filters

Two popular types of sand screens widely used in the oil industry are: slotted liners [16] and wire-wrapped screens (WWS) [8], both with rectangular screen openings, Figure 1. The sand screen acts as an obstacle to prevent the solid particles from flowing into the well. Sand-retention mechanisms, such as particle size-exclusion (see Figure 2) and bridging help this prevention.

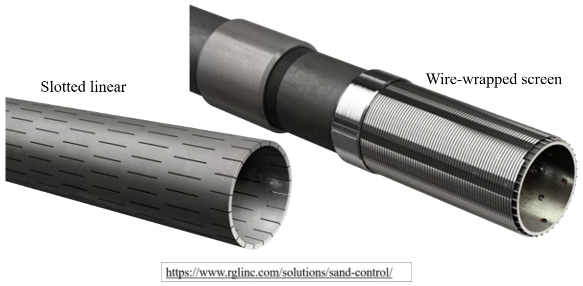

Fig. 1: Slotted liner and wire-wrapped screen widely used in Alberta SAGD wells (adapted from rglinc.com with permission)

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Figure 2 presents the main particles retention mechanisms at a granular scale while having particles larger than 100 μm [6]:

1) Size exclusion mechanism that happens due to large particle size in comparison with the constriction. It is also known as straining.
2) Surface deposition mechanism occurs due to forces existing between the particles and the wall. The roughness [17] of the wall could cause surface deposition mechanism as well.
3) The sequential bridging mechanism that happens following surface deposition.
4) Multi-particle bridging mechanisms could happen due to the high concentration of particles (mechanical bridging) or because of flow convergence at constriction called hydrodynamic bridging.

Among the four mechanisms, multi-particle arching is an efficient sand-retention mechanism that is the main interest of this research.

C. Methodology

This research aims to apply numerical simulations to investigate the solid flow and fluid flow in filter opening and to explore the bridging phenomenon [18]. Coupled computational fluid dynamics (CFD) - discrete element method (DEM) is a promising approach to explore particulate flow in sand screen device and helpful to investigate the interaction forces between the particles and particle-fluid. A CFD-DEM model was applied to investigate the problem. The model was validated with the results of the benchmark problems and the experimental work in the collaborating labs. The details of the CFD-DEM model validation could be found in [19].

II. MATHEMATICAL MODEL OF PARTICULATE FLOW: GOVERNING CONSERVATION EQUATIONS

In this section, fluid flow conservation equations, solid flow conservation equations and coupling approaches are discussed.

A. Fluid Flow Conservation Equations

To simulate fluid flow in sand filters, the conservation equations for mass (continuity equation) and momentum (Navier-Stokes equations (NS)) are solved. In the case of particulate flow, the CFD cells (fluid mesh) are not fully occupied by fluid. In NS equations, the volume occupied by the fluid in each cell is dependent on the volume of the solid particles in that cell.

B. Solid Flow Conservation Equations [20]

The governing equations in DEM for describing translational and rotational motions of individual solid particles are Newton's laws of motion. Both forms of Newton's second law of motion, linear momentum equation and angular momentum equation, are applied as the governing equations. DEM relies on the motion of each particle individually as well as particles' interactions and considers a group of computational points where each point is associated with a physical particle.

In the DEM approach, the contact force acting on a solid particle is calculated using a spring-dashpot system. Dashpots and springs are installed between the two particles to represent the inelastic collision between the two particles and the elastic interaction respectively [21].

C. Coupling Approaches and Grid Resolution

The coupling refers to momentum, heat, and mass exchanges between the continuous phase and the dispersed phase. The important contribution to the particle-fluid momentum exchange is established by the drag force dependent on the granular volume fraction. In contrast to the drag force acting on a single sphere, the granular volume fraction must be considered for the drag force calculation in the CFD-DEM coupling.

1) Zero-way, One-way and Two-way Coupling: There are three general ways of coupling approaches between the solids and the fluid flow:

- Zero-way coupling or uncoupled where dispersed phase and continuous phase evolve independently.
- In one-way coupling, the dispersed phase feels the continuous phase influence and the effect of the dispersed phase on the fluid is not taken into account.
- In two-way coupling, the effects of the dispersed phase on the continuous phase and the effects of the continuous phase on the dispersed phase such as displacement, interphase momentum, mass, and heat transfer are considered.

In all three coupling approaches, the particle-particle interactions and particle-domain interactions have been considered.

2) Coupling and Grid Resolution: From the perspective of the momentum exchange between fluid and particles, CFD-DEM coupling can be of two types: unresolved and resolved. This distinction is based on the method used for calculation of the forces on the particles. Depending on the method used, the resolution of the mesh must be adapted to the size of the particles.

- Unresolved: In this approach, DEM is applied to calculate particle motion without resolving the detailed flow around each particle. Submodels are used to calculate the forces on each particle and the same models are used as momentum sources in the CFD simulation. In unresolved approach, the fluid flow is solved without resolving the flow around the particle. Generally, it means that the mesh is coarser than the particle size. Then the coupling is established by submodels consisting of expressions for the drag force and other forces [22].
- Resolved: Resolved methods simulate the detailed flow around the particles and calculate the forces between the flow and particles without submodels. Resolved methods require a grid much finer than the particle size, and they can also deal with complicated geometries where small grids are necessary to increase the accuracy. Resolved DEM means that the fluid flow around each particle is resolved. Consequently, the coupling between the fluid and the particles is conducted by applying a no-slip boundary condition. There is no need to use submodels

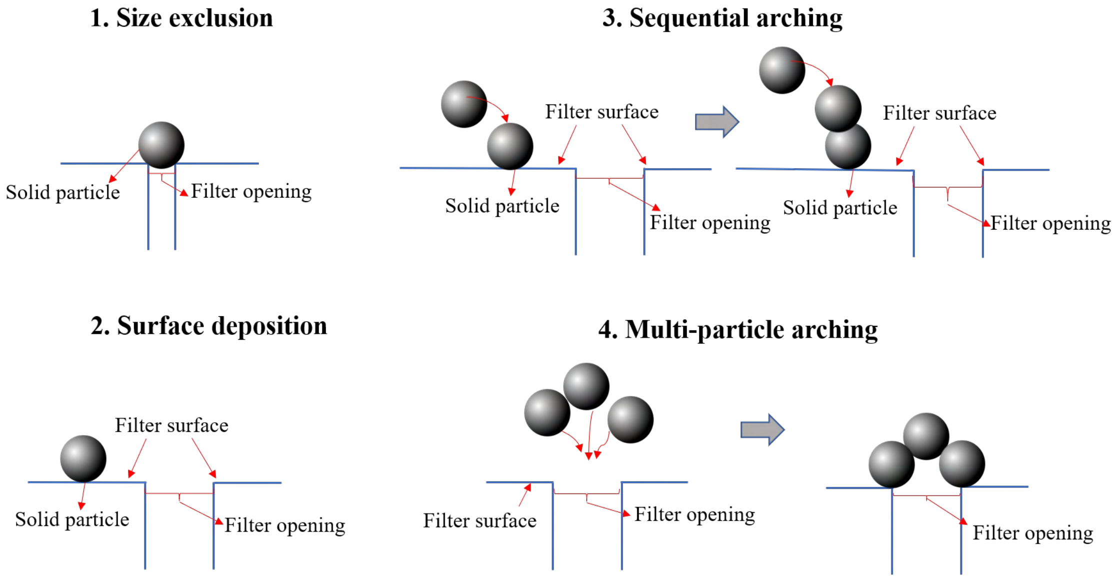

Fig. 2: Schematic illustrating the four main particle retention mechanisms at the filter opening.

to calculate the forces on particles. The forces applied to the particle are due to the application of the no-slip boundary condition at the surface of the particle. For this reason, the grid resolution must be much smaller than the particle size.

In STAR-CCM+, DEM simulations coupled with CFD are always unresolved. But the software allows for continuous mesh refinement, including meshes that are finer than the particle size. The particle equations of motion are based on contact theory and Lagrangian tracking. The particle position is tracked by the Particle Centroid field function, and its shape is also a property of the particle. From these, contact detection algorithms are used to determine when a particle is contacting either another particle or a wall. This is represented by an overlap of the particle with the opposing particle. The force exerted between the particles is a function of the size of the overlap, as well as material properties such as Young's Modulus. Larger overlap means a larger repulsive force between the particles. This calculation is done on a particle by particle basis, with wall contacts using the surface mesh for its geometry. When DEM is coupled with CFD, one or more additional forces are applied to the particle from the CFD results. Usually, this includes a pressure gradient force and a drag force. These forces are calculated based on the data in the cell that the particle centroid is located in. These flow-based forces are applied to the particle as momentum source terms, and together with the contact forces are used to determine the motion of the particle. If the two-way Coupling model is activated, the equal and opposite momentum source term is applied in the CFD model to the cell in which the particle centroid resides.

This unresolved approach will never show a flow redirecting around the surface of a particle, because the particle shape is not resolved.

In STAR-CCM+, when the particle size is smaller than the grid size, the approach will be called "coarse grid unresolved method" or "coarse unresolved" for short in this paper. The case with grid refinement, that is when the particle size larger than the grid size, will be called "smoothed source on refined grid unresolved method" or "smoothed unresolved" for short in this paper if applied.

III. CASE STUDIES

In this section, various scenarios of fluid flow in the packed-bed of sand particles (located on top of the single filter opening) were investigated. Simulations were conducted on wire-wrapped screen (WWS) slot (see Figure 3), and the effect of various parameters and conditions that may contribute to the formation and stability of the multi-particle arch were investigated. In these type of investigations, replication of the simulations matters. The same scenarios were simulated multiple times to ensure that the results were reproducible. These studies were conducted at micro-scale level with several sizes of particles ($50\ \mu m < d_p < 400\ \mu m$) and various shapes. d_p is the particle diameter. Athabasca oil was applied as the viscous fluid in the simulations. Table I presents the computational and mathematical setup of the problem. In the majority of the cases studied in the following sections, multi-particle arching occurred.

IV. SETUP A PACKED-BED OF SAND PARTICLES ON TOP OF THE FILTER OPENING

To form the packed-bed on top of the slot of sand particles, solid particles were injected from top of the domain and injection continued to reach the porosity of the region equal to the assigned number between 0.3 and 0.4.

TABLE I: Mathematical and computational model setup for simulation of particulate flow at filter opening

	Setup
Continuous phase equations	Continuity and NS equations
Fluid phase boundary condition	Top face: fluid velocity inlet = $0.001\frac{m}{s}$
Fluid phase boundary condition	Other faces: no-slip wall
Fluid initial condition (at t = 0)	Quiescent
Discrete phase equations	Newton's 2nd law of motion (conservation of linear and angular momentum)
Particle boundary condition	No-slip wall
Particle initial condition (at t = 0)	Terminal velocity = $0.0065\frac{m}{s}$
Coupling scale	Smoothed unresolved
Coupling technique	Two-way coupling
Particle type	DEM particles, Spherical and polyhedral
Solid particle material	Glass (solid, sand-like)
Fluid material	Athabasca oil
Forces	Pressure gradient force (counts for the buoyancy) Drag force Gravity Interaction forces Lift forces Virtual mass force
DEM model setting	Residence time for particles Track velocity and locations of particles Lagrangian multiphase DEM Multiphase interaction
Grid	3D, Hexahedral
Particle size	$d_p = 200\ \mu m$
Fluid	Athabasca oil ($\mu_f = 0.0136\ Pa \cdot s$ and $\rho_f = 915.2\frac{kg}{m^3}$)
Solid	Glass ($\rho = 2800.0\frac{kg}{m^3}$, Poisson's ratio = 0.45, Young's modulus = 517000.0 Pa)
Fluid time discretization Scheme	Implicit unsteady
Temporal order of discretization	2nd order
Fluid flow solver	Segregated flow
Velocity solver	Algebraic multigrid (AMG) linear solver
Pressure solver	AMG linear solver
Fluid equation of state	Constant density
Continuous phase	Viscous regime and laminar (at slot $Re_f = 0.0672, Re_p = 0.106, St = 0.004$)
CFD time-step	0.01 s
DEM time-step	0.1 s

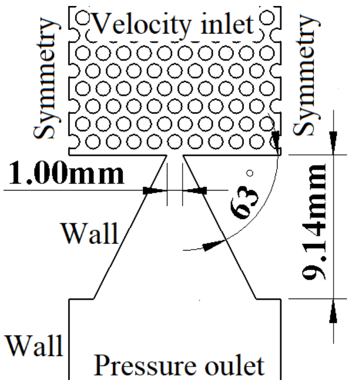

Fig. 3: WWS single opening and assigned boundary conditions in the numerical simulations.

Figure 4 presents how the packed-bed was formed while the slot was closed during particle injection into the bed. Following bed formation, the slot was opened and particles passed through the slot until the arch visibly formed and only very few particles passed through the slot following arch formation.

A. *Simulation of Cases without and with Fluid in Packed-bed*

The role of fluid was investigated in multi-particle arch formation. Four cases were studied with no fluid, as well as three fluid cases with various thermophysical properties: air, water and Athabasca oil. In all cases studied, the arch formed with/without fluid, broke after a period of time and reformed again, and this pattern continued. Without fluid, the arch formed faster; however, it stayed stable for a shorter period of time and reformed more quickly after breakage. In this case, it seems that the particle-particle interaction force and the gravity force played key roles in arch formation. Arch formation without fluid leads to the conclusion that particle-fluid interaction forces might not be essential for multi-particle bridging at micro-scale.

Figure 5 presents arch formation, breakage and reformation.

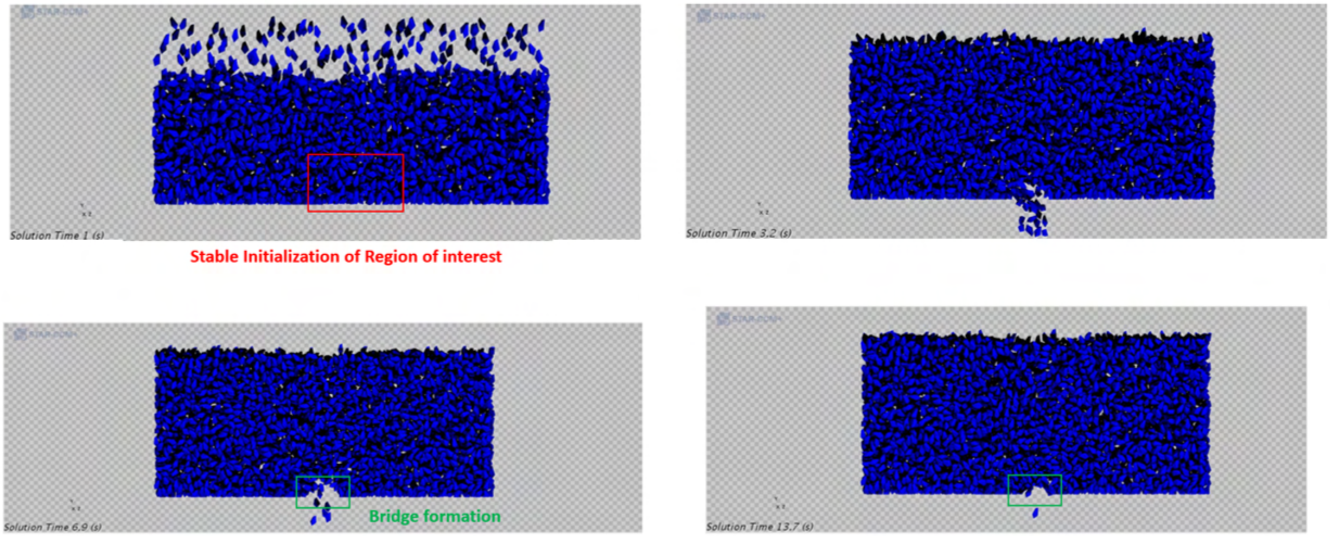

Fig. 4: Packed-bed formation of sand particles with a closed slot and bridge formation after opening the slot.

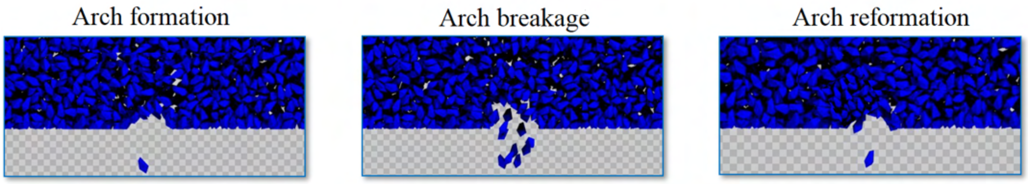

Fig. 5: Arch formation, destruction and reformation at sand filter opening.

B. Simulation of Cases with Spherical and Polyhedral Particles

In this section, the CFD-DEM simulations were conducted with spherical and polyhedral particles. The objective was to investigate the effect of the particles' shape on arch formation and stability. The study was done on WWS with polyhedral particles and different aspect ratios (AR). In all cases, multi-particle arching occurred with both spherical and polyhedral particles. With non-spherical particles, the arch formed faster and stayed stable for a longer time than the case with spherical particle. For non-spherical particles with higher aspect ratio of 2.3, the arch was less stable than the case with the lower aspect ratio of 1.6.

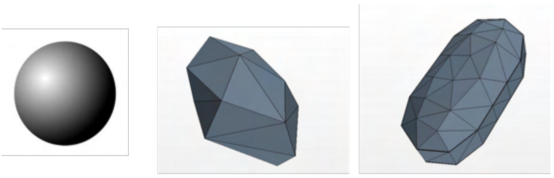

Fig. 6: Particle shapes with aspect ratios from left to right: 1, 1.6 and 2.3

C. Simulation of the Packed-bed Cases with Particle Size Distribution

In this section, the objective was to investigate the effect of the particle size distribution on arch formation and stability. Table II presents the monitored times (in seconds) for when multi-particle arching happened, broke and reformed at WWS opening. The stabilization and reformation periods are also presented. With the uniform spherical case, it took longer for the arch to form. Arch stayed stable for a shorter period of time compare to the polyhedral cases. It also took longer for the arch to reform after breakage in comparison with the polyhedral cases. With polyhedral particle size distribution at micro-scale, the initial formation of the multi-particle arch took longer than the case with the uniform-size distribution. With PSD case, the arch stayed stable for a longer time than the uniform cases (both polyhedral and spherical). Following arch breakage, it took longer to reform the arch compared to the uniform-size cases.

D. Packed-Bed Cases with Added Reservoir Load

In this section, the stress of the reservoir was added to the packed-bed in different ways to investigate its effect on the region close to the slot and on the multi-particle arch behavior. Guo et al. [23] studied the effect of the stress in a large-scale unconsolidated sand pack over a multi-slot coupon of the slotted liner. The experimental results showed that the

TABLE II: Monitored times (in seconds) for when multi-particle arching happened, broke and reformed at a WWS opening comparing uniform and PSD cases.

	Spherical particle (AR = 1), uniform	**Polyhedral particle (AR = 1.6), uniform**	**Polyhedral particle (AR = 1.6), PSD**
Arch formed	12.43	8.65	9.13
Arch broke	16.08	13.58	14.81
Arch reformed	20.38	17.47	19.23
Stabilization period	3.65	4.93	5.68
Reformation period	4.3	3.89	4.42

slotted liner performance is significantly affected by the stress of the packed-bed on the liner. They concluded that the higher stresses help stabilize the sand bridges over the slots which result in less sand production. Fattahpour et al. [24] also studied the effect of the increasing stress on the performance of the sand filter. They applied varying levels of stress to the sand-packs around the slotted liner in parallel and perpendicular to the multi-slot coupon. With increased stress, they reported a reduced amount of the sand production.

The approaches taken, to test the effect of the increased reservoir load, are as follows:

1) The height of the unconsolidated region, that is the height of the packed-bed, was increased to replicate the stress of the reservoir and to add stress on the slot region under two circumstances:
   - All particles were sand particles size-wise and property-wise.
   - Particles added, to increase the height of the unconsolidated region, were huge particles heavier than sand (see Figure 7).

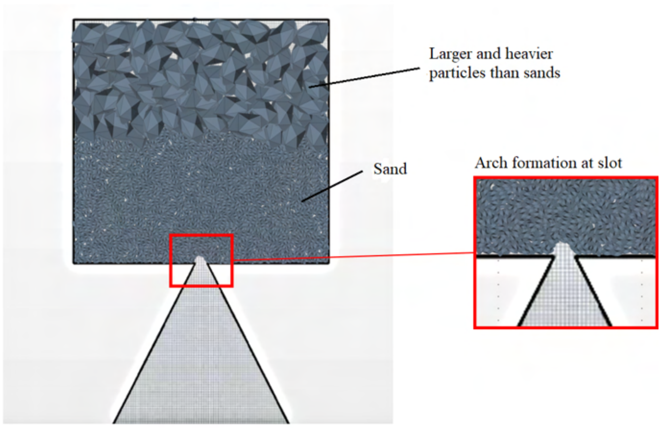

Fig. 7: Increasing stress load by increasing the height of unconsolidated region with heavier and larger particles than sand.

In all cases tested, multi-particle arch formed, stayed stable, broke and reformed. The increased height resulted in increased stress over the unconsolidated region near the slot. The increased height with heavy and large particles resulted in a larger increase of the stress load than the increased height with sand particles. As the stress load increased, the arch formed faster, and it was stable for a longer period of time in comparison with the lower stress load cases. It took shorter for the multi-particle arch to reform after breakage for the cases with increasing stress load. The numerical results were in agreement with the experimental results presented in [23] and [24].

V. SUMMARY AND FUTURE WORK

The key contributions of the present research, that improved our understanding of the arching phenomenon as an efficient sand retention mechanism, are summarized as follows:

1) The computational fluid dynamic (CFD) - discrete element method (DEM) model is cable of predicting multi-particle arch formation, stabilization, breakage and reformation under steady conditions of the well-bore.
2) The load stress from the packed-bed of solid particles on top of the slot opening is essential to form the multi-particle arch. The increased stress results in multi-particle arch formation/reformation in a shorter time and arch stabilization for a longer time, that is, improved sand retention.
3) Particle size distribution supports the multi-particle arch stabilization and it stays stable for a longer time than the case with the uniform size distribution.
4) Particle shape affects the arch stability. Non-spherical particles with sharp corners result in a more stable arch, but aspect ratio should not be too large.

Finally, areas for further research were identified.

1) Calculate and add the stress of the reservoir based on the soil mechanics to the model and investigative its effect on arching.
2) Include other reservoir fluids in the multi-phase simulations including water, steam and gas and study arching further considering multi-phase fluid flow.
3) Consider energy equation and temperature changes in the simulations and study arching with respect to temperature alteration.
4) Explore the effect of multiple slots on arch formation and stabilization.
5) Investigate different screen opening designs with various geometries that could improve plugging prevention and

support the multi-particle arch formation and stabilization.

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APPENDIX A: DEFINITIONS OF TERMS

Oil sand and SAGD - Oil sand is a highly viscous mixture ($> 10,000\ cP$) of sand, clay, water, and bitumen [25]. This viscous oil is also called heavy oil and is immobile under reservoir conditions. Steam-assisted gravity drainage (SAGD) is a heavy oil recovery technique broadly used in Alberta, Canada. In SAGD operations, there are two horizontal wells drilled in the depth of about 300 meters in the reservoir. The wells are five meters apart, and their length is between 500 to 1000 meters. Steam is injected into the top well injection well to warm up the formation and lower the viscosity of the heavy oil. Due to gravity, heated oil flows down to the production well located underneath the injection well and get produced to the surface [26].

Sand production and sand screen - In most oil sand reservoirs, sand is produced with oil. Control and mitigation of sand production are crucial to achieving maximum well productivity as well as wellbore stability.

Sand control - Sand control, also known as sand-retention, refers to the utilization of screens to cut down the sand production risks. Slotted liners (SL) and wire-wrapped screens (WWS) are two types of sand control devices commonly used for thermal oil sands recovery operations, such as SAGD, in both injection and production wells [16].

Failure mechanisms - Particle buildup and plugging (clogging) at the entrance and throughout the length of the sand screen opening (for instance slot or WWS aperture), are the common failure mechanism in sand screen devices. Plugging in sand screen device is the reduction in the open flow area of the sand control media due to trapped sand and fines and different types of scale. It will decline the production and increase the draw-down pressure. Particle buildup also happens due to the transport of particles less than ($44\mu m$) known as fines [6]. This process is referred to as fines migration. Migration, the buildup of fines and bridging could cause the plugging in the pore throats of formation and the plugging near the opening of the sand control device. This phenomenon decreases the permeability and productivity of the reservoir as well as quality performance of the sand screen device.

Granular system - Granular systems consist of commonly discrete solid and macroscopic particles ($> 100\mu m$) that interact with each other closely [6]. These systems are motivating topics of research due to their complicated rheology and showing special phenomena such as bridging and jamming [27].

They are broadly used in various industries, such as mining, oil, and gas, food and medicine. Accordingly, understanding and modelling of granular systems is an interdisciplinary research area. In most of the granular systems, fluid (gas or liquid) drives the solid particles also known as particulate flow or particle-laden flow. An example of this in heavy oil recovery techniques is the sand transport and sand-retention in down-hole completions. A recognized aspect of the particulate flow is plugging or jamming which occurs in the media that particulate fluid flows as well as at the filter screen possibly used for filtering the particles. Multi-particle bridge formation on filter opening reduces the chance of plugging.

Bridging - Bridging theory and laboratory tests show that particles will bridge on a screen (filter) opening and this phenomenon will help sand control and prevent plugging [4]. The multi-particle bridging phenomenon can be seen in Figure 2. There are definitions that help to understand and investigate bridging based on Coberly's definitions [4]. "A stable bridge is defined as a bridge which, when broken, will reform nearly fast on a stable opening. A stable opening is a screen opening size on which a stable bridge will form. The maximum opening is a screen opening size on which a bridge will not form even by obstructing the opening. The bridging range is defined as the ratio of the maximum opening to the stable opening. The bridging grain size is the spherical particle diameter which would form a stable bridge on a given filter opening" [4].