#### **ORIGINAL PAPER**



# Localized dissolution in sediments under stress

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## Abstract

Mineral dissolution and subsurface volume contraction can result from various natural and engineered subsurface processes. This study explores localized granular dissolution in sediments under constant vertical stress and zero lateral boundaries using 2D and 3D discrete element simulations to gather macro-scale and particle-scale information during dissolution. Local arches form when the dissolving inclusion size is similar to the grain size; however, granular chains buckle and grains flow to refill voids when dissolving inclusions are larger than the length scale of force chains (about 6-to-10 grain diameters). Force chains arch around the region that undergoes grain dissolution; interparticle contact forces are low within the contracting zone, yet are sufficient to provide transverse support to the major force chains. Higher granular interlocking leads to the formation of more pronounced force arches, results in higher internal porosity, and limits the vertical contraction. The vertical contraction and the global porosity increase proportionally to the lost solid volume, but remain below the upper bounds computed for dissolution at either constant internal porosity or constant global volume. The sediment porosity evolves towards a terminal porosity that is defined by granular interlocking; the minimum mass loss required to reach the terminal porosity can exceed 10-to-15%. The global stress ratio  $K_0$  decreases during the early state of dissolution and in sediments with high interlocking; otherwise, it evolves towards a steady value that can be as high as  $K_0 \approx 0.7$  to 0.8; this stress ratio is compatible with the horizontal reaction required to stabilize the internal force arches.

**Keywords** Granular dissolution  $\cdot$  Soluble granular inclusions  $\cdot$  Deep cavities  $\cdot$  Granular arching  $\cdot$  Discrete element method  $\cdot$  Tunnels  $\cdot$  Hydrates  $\cdot$  Carbon storage

# 1 Introduction

Localized dissolution and volume contraction can result from various engineered and natural subsurface processes, including: tunneling and mine collapse [5, 72], dissolution in calcareous terrains [71], decementation and softening [75], and the dissociation of hydrate nodules or melting of segregated ice lenses [44]. Localized dissolution induced

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<sup>2</sup> Earth Science and Engineering, King Abdullah University of Science and Technology (KAUST), Thuwal, Saudi Arabia by reactive fluid flow takes place when the rate of advection exceeds the rate of diffusion and the rate of reaction [23, 27, 33, 34, 53]. Pre-existing discontinuities, stratigraphy, the state of stress, mixed mineralogy and marked changes in fluid chemistry contribute to the development of localized dissolution [11, 21, 26].

Pressure solution is a common dissolution process that involves the preferential dissolution of minerals at grain contacts followed by diffusive mass transfer to the surrounding pores [22, 52, 59]. It is a major diagenetic process that contributes to sediment compaction and porosity changes [2, 12, 64], and is an important mechanism in soil and rock creep [41, 48]. Stylolites are salient rock features associated with volume reduction by pressure solution [6, 20, 37, 38, 54, 66].

Dissolution is typically slow in nature, however, human activity can rapidly move natural systems far from equilibrium and trigger dissolution in relatively short time-scales. Carbon geological storage is a case in point: injected  $CO_2$  acidifies the pore water and triggers mineral dissolution, porosity changes, settlement, and may also result in tensile

fracturing of seal layers [18, 39, 42, 57, 74]. Other examples range from fast dissolution caused by high hydraulic gradients beneath dams [15, 30, 55], to gas hydrate dissociation driven by climate change and ensuing submarine landslides [24, 63, 70]. These examples highlight the inherent hydrochemo-mechanical coupled nature of mineral dissolution, and underlying changes in stiffness, strength and permeability [43, 58, 60, 65].

Localized dissolution resembles cavity contraction. Available continuum solutions by Eshelby [17] are appropriate solutions for cohesive continua such as intact rocks [16, 28, 45]. However, there is limited information on the effects of cavity contraction in uncemented granular materials. This research investigates the consequences of localized volume contraction in sediments under stress using the Discrete Element Method, DEM. The study includes both 2D and 3D simulations.

## 2 Numerical simulation

We explore the consequences of dissolution using 2D and 3D DEM simulations using the commercially available Particle Flow Code PFC-2D and 3D by Itasca. Circular disks (2D simulations) and spheres (3D simulations) have a uniform size distribution. 2D simulations use a linear contact model and 3D simulations use the non-linear Hertzian contact model. Table 1 summarizes material properties and simulation conditions. Table 2 outlines the parametric study. The representative elementary volume REV is subjected to constant vertical stress and zero-lateral strain boundary conditions to resemble horizontally repetitive inclusions (Fig. 1).

Table 2 Parametric study (total: 36 simulation conditions)

	Conditions	
Parameters		
Dimension	2D and 3D	
Relative zone size D/L	0.2, 0.4 and 0.6	
Soluble fraction SF <sup>a</sup>	50% and 100%	
Hindered rotation HR <sup>b</sup>	0%, 40%, and 80%	

<sup>a</sup>Percentage of particles within the inclusions that experience size reduction

<sup>b</sup>Percentage of particles with hindered rotation in the REV

## 2.1 Granular interlocking

Grain angularity promotes interlocking and rotational resistance. Earlier efforts to capture the effects of grain angularity hindered particle rotation [4, 62]; this approach is computationally efficient but may result in unrealistically high friction angles and dilatency when all particles are affected. Other alternatives to reproduce particle angularity effects include the application of rolling resistance at contacts [25, 35, 50] and simulations with clusters and non-spherical particles [29, 46, 73]. Given the high computational demands required for stable mineral dissolution studies, we adopt the numerically efficient hindered rotation but limit it to a pre-set fraction HR of randomly located particles ranging from HR = 0 to 80% (see [8] for a detailed discussion and calibration).

## 2.2 Specimen preparation

Particles nucleate at random locations, and gradually expand within the 2D square and 3D cubic cells under zero gravity and zero interparticle friction until they reach their target size (a similar approach to [3]). Then, friction and gravity

	Properties	2D (disks)	3D (spheres)
Particles	Particle size distribution	Uniform size distribution $(d_{min} = 0.8 \text{ mm}, d_{max} = 1.2 \text{ mm})$	Uniform size distribution $(d_{min} = 2 \text{ mm}, d_{max} = 3 \text{ mm})$
	Number of particles	10,567 disks	9167 spheres
	Particle density	2650 kg/m <sup>3</sup>	$2650 \text{ kg/m}^3$
	Contact models	Linear contact model	Hertzian contact model
		-Normal stiffness $kn = 10^8$ N/m	-Shear modulus = $2.9 \times 10^9$ Pa
		-Shear stiffness ks = $10^8$ N/m	-Poisson's ratio $= 0.3$
	Inter-particle friction	0.5	0.5
Boundary conditions	Initial cell size	$100 \text{ mm} \times 100 \text{ mm}$	$50 \text{ mm} \times 50 \text{ mm} \times 50 \text{ mm}$
	Vertical stress during dissolution	100 kPa	100 kPa
	Lateral boundaries	Zero strain	Zero strain
	Particle/wall friction	0	0

Fig. 1 Initial size of the dissolvable zones in a representative element volume. Red grains are soluble (all cases shown are for soluble fraction SF = 100%). A and V are total area and volume including the inclusions. *Note* \* d is the particle diameter (color figure online)



are turned on, and the sediment is incrementally subjected to vertical stress through rigid top and bottom caps to reach 100 kPa under zero lateral strain boundary conditions (note: there is no friction between grains and walls).

## 2.3 Dissolution under stress

Soluble grains occupy a circular (2D simulations) or spherical (3D simulations) zone of size D at the center of the REV of size L (Fig. 1). The fraction of soluble particles within the contracting zone is either SF=50% or 100%. Simulations include three different D/L ratios; the case of D/L=0.2 represents sparsely populated dissolving zones with minimal interaction, while the case of D/L=0.6 corresponds to interacting near-neighbor zones. Clearly, 3D volume ratios  $\pi/6 \cdot (D/L)^3$  are smaller than 2D area ratios  $\pi/4 \cdot (D/L)^2$  for the same size ratio D/L (Fig. 1).

Selected particles SF in the contracting zone are "dissolved" by simultaneously reducing their radius at the same rate. Size reduction must be very gradual to minimize inertial effects: typically, the radius reduction in each step is  $\Delta R_i = R_0/50,000$  where  $R_0$  is the initial radius. Furthermore, we require that the ratio of the mean unbalanced force to the mean contact force remains lower than 0.001 to ensure stable conditions throughout the dissolution process. The physical time for the dissolution simulations is about 1 min, however, the computation time often exceeds several weeks.

The inertial number I is the ratio between the time for a given displacement when accelerated by the stress-dependent skeletal forces  $\sigma' d^2$  and the time for the same displacement given an imposed strain rate  $\dot{\gamma}$  [13, 49]:

$$I = \frac{\dot{\gamma}d}{\sqrt{\sigma'/\rho}} \tag{1}$$

For particles of diameter d = 1 mm, grain density  $\rho = 2700 \text{ kg/m}^3$ , average effective stress  $\sigma' = 100 \text{ kPa}$ , and inclusion shrinking rate  $\dot{\gamma} = 0.008/\text{s}$ , the computed inertial number  $I \approx 10^{-6}$  is well within the quasi-static criterion  $I < 10^{-3}$  for strain rate independent frictional resistance [49].

## **3 Results**

Simulation results provide macro-scale parameters (global porosity, vertical displacement, and stress ratio  $K_0$  measured at boundaries) as well as particle-scale information (contact forces and force chains, coordination number and particle displacement). We present the evolution of these parameters as a function of the normalized size reduction  $\Delta R/R_0$  of soluble particles, which is equivalent to the progression of physical time normalized by the total physical time.

## 3.1 Global parameters

Both the vertical contraction  $\delta$  and the global porosity increase in proportion to the lost solid volume, which combines the contractible zone size D/L, the soluble fraction SF and the extent of dissolution  $\Delta R/R_0$  (Fig. 2 for 2D simulations, and Fig. 3 for 3D simulations). Higher sediment interlocking limits the vertical displacement and results in higher internal porosity. These results hint to pronounced fabric changes taking place within the REV.



**Fig. 2** Normalized vertical displacement, global porosity, and equivalent global stress ratio  $K_0$  during localized dissolution. 2D simulations for a SF=50% fraction of soluble particles in the contractible zone

While the average vertical stress  $\sigma_v$  remains constant in this study, the horizontal forces that act against the fixed lateral boundaries evolve during dissolution. Let's compute the equivalent horizontal stress  $\sigma_h$  as the sum of all contact forces against lateral walls divided by the wall area at a given dissolution step (or height in 2D). Results displayed in Figs. 2 and 3 show:

 The initial stress ratio K<sub>0</sub>=σ<sub>h</sub>/σ<sub>v</sub> for the 3D simulations is K<sub>0</sub>=0.43; this value is in line with soils with a friction angle of 35° (Jacky's equation—[47]).

- There is an early transient drop in K<sub>0</sub> in packings with high interlocking and/or large contractible zones.
- Eventually, the global stress ratio  $K_0$  increases with dissolution towards a steady value that can be as high as  $K_0 \approx 0.7$  to 0.8, except for 3D packings with high interlocking.

Similar behaviors were observed in both experimental and numerical results when specimens experienced the dissolution of randomly distributed soluble particles [8, 39, 61].



Fig. 3 Normalized vertical displacement, global porosity, and equivalent global stress ratio  $K_0$  during localized dissolution. 3D simulations for a SF=50% fraction of soluble particles in the contractible zone

## 3.2 Particle-scale response

Grains adjacent to the contracting zone flow towards the shrinking volume and refill it so that no cavity remains after dissolution, in agreement with the cohesionless nature of the sediment (Fig. 4a—see a time evolution in the Supplementary Material). Most of the refilling takes place from the sides. Increasing granular interlocking lessens the grain displacements around the shrinking volume. Force chains are evenly distributed before dissolution and have a preferentially vertical orientation in agreement with the initial stress ratio  $K_0 = 0.48$ . Force redistribution starts immediately after the dissolvable particles begin to contract. Force chains arch around the region that experiences grain dissolution; higher granular interlocking results in more pronounced arches (Fig. 4b). Interparticle contact forces are low within the contracting zone, and they are preferentially transverse to the major force chains to prevent their buckling (see



**Fig. 4** Displacement vectors and contact force chains after dissolution. 2D simulations for a SF=50% fraction of soluble particles in the inclusions. Black circles show the original size of the contracting zone. *Note* Displacement vectors and contact force chains are shown at the same scales for all cases for accurate comparison



**Fig. 5** Local porosity and coordination number inside the contracting zone. The large filled circles show the initial conditions for the 3D  $(n_0=0.38, cn=5.36)$  and 2D simulations  $(n_0=0.167, cn=3.64)$ . The stars correspond to the 3D simple cubic packing (n=0.476, cn=6) and the 2D square packing (n=0.215, cn=4). Filled green markers: SF=100%; empty markers: SF=50%. Marker shape: circular HR=0%, square HR=40%, diamond HR=80% (color figure online)

also [10]). The affected zone increases outwards towards the REV boundaries during dissolution; eventually, the zone that is strongly influenced by local dissolution exceeds the initial size of the contracting inclusion (Fig. 4b).

Figure 5 plots the local porosity n versus the coordination number cn within the contracting zone for both 2D and 3D simulations (note: the PFC code distinguishes 'real' from 'virtual' contacts where the inter-particle separation is less than  $10^{-6}$  times the mean radius; while virtual contacts are necessary for equilibrium, we use real contacts to compute the coordination numbers reported in Fig. 5 to emphasize grains that are actively involved in the granular skeleton). The filled black circles show the initial conditions. The local porosity increases and the coordination number decreases with the extent of dissolution (empty symbols for soluble fraction SF = 50% and filled symbols for SF = 100%) and reach values that exceed the 3D simple cubic and 2D square packings which are the extreme loose configurations for frictionless mono-size particles. Interlocking hampers granular displacement and leads to higher porosity within the dissolution affected zone (compare circular symbols HR = 0% with squares HR = 40% and diamonds HR = 80%). The general trend confirms the inverse relationship between porosity and coordination number.

## 4 Analyses and discussion

Numerical results reported in the previous section show that localized dissolution leads to stress and porosity conditions that deviate from standard sedimentation. These site conditions challenge the interpretation of in situ characterization data, such as penetration resistance and shear wave velocity [7, 40], and the prediction of engineering properties [8, 9, 19, 67, 68]. In this section we analyze the complete numerical dataset to gain additional information about the evolution of localized dissolution in sediments under stress.

## 4.1 Boundary effects

The REV tested in these simulations is subjected to constant vertical stress and zero-lateral strain boundary conditions (Fig. 1). Forces and displacements show that the dissolving zone interacts with the boundaries, particularly for large D/L cases (Fig. 4). Saint–Venant's principle, theoretical solutions such as Kirsch and experimental evidence from cone calibration studies suggest that the distance to the boundaries has to be multiple times larger than the size of the contracting zone to avoid boundary effects. All these observations confirm that the simulated conditions best correspond to repetitive contractive zones with an internal scale L.

#### 4.2 Relative scales: D/d

The ratio between the inclusion diameter and the grain diameter D/d defines various perturbation modes. Simulations conducted as part of this study range from D/d=4 (D/L=0.2 under 3D conditions) to D/d = 60 (D/L = 0.6 under 2D conditions—Fig. 1).

The inert particles jam and local arches form as  $D/d \rightarrow 1$ . The stable arches bridge internal voids where particles can sit with minimal coordination (see Fig. 5). This regime resembles stable arch formation against cavities of size O; published results show that the ratio O/d varies with granular interlocking and ranges from O/d=3-to-5 for smooth glass beads to D/d=5-to-6 for more angular grains [1, 69, 78].

Conversely, large dissolving cavities  $D/d \gg 1$  affect length scales larger than local force chains (typically ~ 6-to-10 d) and induces macro-scale effects. The internal porosity evolves towards a terminal condition where additional dissolution causes chain buckling and densification, and dissolution advances at a constant terminal porosity (see data for dissolution of randomly distributed dissolving particles in [7]).

## 4.3 Comparing 2D and 3D simulation results

Direct comparisons between 2D and 3D simulation results are inherently limited by geometric differences (2D tunnel vs. 3D spherical-shaped contractive zones), and differences between the packing of grains and disks, namely: porosity, coordination for stability, rotational frustration and mobility. However, results in Figs. 2, 3, and 5 show parallel trends for all global and grain-scale parameters analyzed in this study. Some differences reflect the distinct D/d ratios in 2D and 3D simulations, as discussed above, and the more pronounced consequences of hindered rotation on mobility (3 degrees of freedom are lost in 3D vs. only 1 rotational degree of freedom in 2D—Fig. 5).

## 4.4 Limiting contraction and porosity

We can obtain an upper bound estimate of the normalized vertical displacement  $\delta_i/L$  at the ith-dissolution step by assuming dissolution at a constant internal porosity  $n_0$ 

$$\frac{\delta_i}{L} = \frac{\Delta V_s}{V_{so}}$$
(2a)

$$\frac{\delta_i}{L} = \frac{\pi}{6} \left(\frac{D}{L}\right)^3 SF\left[1 - \left(1 - \frac{\Delta R_i}{R_o}\right)^3\right] \text{ for 3D configuration}$$
(2b)

$$\frac{\delta_i}{L} = \frac{\pi}{4} \left(\frac{D}{L}\right)^2 SF\left[1 - \left(1 - \frac{\Delta R_i}{R_o}\right)^2\right] \quad \text{for 2D configuration}$$
(2c)

where  $\Delta V_s$  is the change in the volume of solids and  $V_{so}$  is the initial volume of solids in the REV. Plots in Fig. 6a show the computed upper boundaries and numerical results

for the 36 cases. The horizontal axis is the dissolution factor in Eq. 2:  $(D/L)^2$ SF for 2D and  $(D/L)^3$ SF for 3D simulations. Data points for SF = 50% and SF = 100% collapse onto single trends. Each trend line corresponds to granular interlocking. Trends are lower than the upper-bound, the gap increases with HR, but tends to become parallel for high dissolution factors, as clearly seen in 2D results.

Clearly, the granular packing must experience an increase in porosity. Then, let's compute the upper bound increase in porosity by assuming that the global volume remains constant  $V_T$  = const., hence, there is no contraction  $\delta$  = 0; at the ith-step:

$$n_i = n_0 + \frac{\Delta V_s}{V_T} \le n_T \tag{3a}$$

$$n_i = n_0 + \frac{\pi}{6} \left(1 - n_0\right) \left(\frac{\mathrm{D}}{\mathrm{L}}\right)^3 \mathrm{SF} \left[1 - \left(1 - \frac{\Delta \mathrm{R}_i}{\mathrm{R}_o}\right)^3\right]$$
(3b)

for 3D configuration

$$n_i = n_0 + \frac{\pi}{4} (1 - n_0) \left(\frac{\mathrm{D}}{\mathrm{L}}\right)^2 \mathrm{SF} \left[1 - \left(1 - \frac{\Delta \mathrm{R}_i}{\mathrm{R}_o}\right)^2\right]$$
(3c)

for 2D configuration

The inequality in Eq. 3a captures the limiting terminal porosity  $n_T$  required for internal equilibrium [51]. Plots in Fig. 6b shows the full numerical dataset and the computed porosity upper-bounds. Once again, hindered rotation HR defines the different trends and data points for SF=50% and SF=100% collapse onto single trends for the same HR. Computed porosities are closer to the upper bound when granular interlocking is high. More importantly, trends evolve to different terminal porosities as a function of their granular interlocking (better seen in the 2D results—Fig. 6b–i).

Differences between numerically computed contraction and porosity trends and the analytical upper bounds are consistent with the development of load-carrying grain arches around the dissolving particles, which are favored by high grain interlocking.

## 4.5 Dissolution threshold

Contraction tracks grain dissolution for high volume fractions of dissolvable grains, as the sediment reaches a terminal porosity  $n_T$  (Fig. 6b); thus, any additional dissolution will be accompanied by volume contraction to maintain  $n_T$ . The volume of dissolved mass relative to the initial volume of solids  $\Delta V_s/V_{so}$  required to reach the terminal porosity  $n_T$  depends on the initial porosity  $n_0$ 

$$\frac{\Delta V_{s}}{V_{so}} = \frac{V_{To}(1-n_{0}) - V_{Tf}(1-n_{T})}{V_{To}(1-n_{0})} \ge \frac{n_{T}-n_{0}}{1-n_{0}}$$
(4)





**Fig. 6** Normalized vertical displacement  $\delta/L$ , global porosity, and equivalent global stress ratio  $K_0$  as a function of the extent of dissolution in terms of the dissolution factor  $(D/L)^2SF$  for 2D or  $(D/L)^3SF$  for 3D simulations. Thick black lines: upper bound trends (Eqs. 2, 3).

Trend lines connect markers for cases with the same hindered rotation HR. Markers: empty=SF=50%, filled=SF=100%. *Note* all values correspond to  $\Delta R/R_0=80\%$ 

The inequality establishes the lower bound for  $\Delta V_s/V_{so}$  when dissolution takes place at a constant total volume  $V_{To} = V_{Tf}$ . For example, an increase in porosity from  $n_o = 0.4$  to  $n_T = 0.46$  would require a loss in solid volume of  $\Delta V_s/V_{so} \ge 10\%$ . Numerical results for the localized dissolution cases presented in this manuscript suggest  $\Delta V_s/V_{so} \ge 15\%$  (Fig. 6a, b). Experimental results obtained for the dissolution of randomly distributed soluble particles show ratios  $\Delta V_s/V_{so} \ge 10\%$  [61].

#### 4.6 Stress ratio K<sub>0</sub>

Lateral stress relaxation takes place during the early stages of dissolution and in packings with high interlocking (see the complete dataset in Fig. 6c). The force arches that form around contracting cavities resemble a "hinged arch"; the analysis in terms of the horizontal force required to stabilize an arch with a distributed vertical load  $q = \sigma_v$  leads to an equivalent lateral stress ratio

$$K_0 = \frac{\sigma_h}{\sigma_v} = \frac{1}{2} \tan^2 \beta \tag{5}$$

where  $\beta$  is the angle between the center of the loading plate and center of the of the lateral boundary and evolves as contraction takes place  $\tan\beta = (1 - \delta/L)^{-1}$ . This simple 2D analysis suggests that the stress ratio will increase during dissolution, from K<sub>0</sub>=0.45 before contraction ( $\delta/L=0$ ) to K<sub>0</sub>=0.62 as dissolution progresses and contraction reaches  $\delta/L=0.1$ . Clearly, the granular medium is more complex than a hinged arch as highlighted by data trends in Fig. 6c.

# 4.7 Comparing cohesive media and frictional granular matter

A circular cavity in an elastic medium subjected to far field stresses  $\sigma_v$  and  $\sigma_h = K_0 \sigma_v$  experiences the following extreme hoop stress (for  $0 \le K_0 \le 1$ ):  $\sigma_{\theta}|_{max} = (3 - K_0)\sigma_v$  at the springline, and  $\sigma_{\theta}|_{min} = (3K_0 - 1)\sigma_v$ . Similarly, the extreme hoop stresses on the wall of a spherical cavity subjected to farfield stresses  $[\sigma_v, \sigma_h, \sigma_h]$  are:  $\sigma_{\theta}|_{max} = (2 + 1.5K_0)\sigma_v$  and  $\sigma_{\theta}|_{min} = (4K_0 - 0.5)\sigma_v$  (Kirsch solution—[14, 36, 56]). The stress anisotropy is infinite at the wall; in the case of boreholes, breakouts take place at the springline and typically involve conjugate shear fractures and successive spalling [31, 32, 76, 77].

Uncemented granular media can sustain a limited stress anisotropy  $K_f = tan^2(45^\circ + \phi/2)$  in agreement with the frictional Coulomb failure criterion. Yet, similarly to borehole breakouts in cohesive media with  $K_0 < 1$ , cave-ins occur mainly from the sides, i.e., the springline (Fig. 4a), and often exhibit displacement discontinuities or shear bands.

# 5 Conclusions

Subsurface volume contraction can result from various natural and engineered subsurface processes. In this paper, we explored the consequences of localized dissolution in sediments using 2D and 3D discrete element simulations where the granular medium was subjected to constant vertical stress and zero-lateral strain boundary conditions. Simulation results provide the evolution of macro-scale and particle-scale parameters during dissolution.

Force redistribution starts as soon as the dissolvable particles begin contracting. The ratio between the inclusion diameter and the grain diameter D/d defines various perturbation modes. Local arches form when D/d  $\approx$  1 and leave a void inside. Conversely, large dissolving zones D/d  $\gg$  1 exceed the length scale of local force chains (D > 6-to-10d), cause chain buckling and grains flow into refill the void. Marked force chains arch around the region that experiences grain dissolution, interparticle contact forces are low within the affected zone, and they are preferentially normal to the major force chains to prevent their buckling.

Higher granular interlocking leads to the formation of more pronounced force arches, results in higher internal porosity, and limits the vertical contraction. The vertical contraction and the global porosity increase proportionally to the lost solid volume. The upper bound estimate for the vertical contraction corresponds to dissolution at a constant internal porosity. The upper bound increase in porosity assumes that the global volume remains constant, but it is limited by equilibrium at terminal porosity. The terminal porosity increases with granular interlocking. Differences between numerical results and the analytical upper bounds are consistent with the development of loadcarrying grain arches around the dissolving particles. The mass loss required to reach the terminal porosity can exceed 10-to-15%.

Lateral stress relaxation and a reduction in  $K_0$  take place during early stages of dissolution in media with high interlocking. In other cases, the global stress ratio  $K_0$  increases towards a steady value that can be as high as  $K_0 \approx 0.7$  to 0.8. This stress ratio is compatible with the horizontal reaction required to stabilize a hinged arch, i.e., the internal granular arches within the granular medium.

Grains adjacent to contracting zones move towards the shrinking volume and no cavity remains after dissolution. Preferential horizontal flow resembles borehole breakouts and the stress concentration and failure along the springline in tunnels.

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## **Compliance with ethical standards**

**Conflict of interest** The authors declare that they have no conflict of interest.

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