Supplementary Information for

Unearthing real time 3D ant tunneling mechanics

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Supplementary text
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Legends for Movies S1 to S4
SI References

Other supplementary materials for this manuscript include the following:
Movies S1 to S4
Supporting Information Text

Constructing Experimental Apparatus. The testing apparatus was first designed and built at Caltech. This device consisted of a small plastic container which could be filled with sand and ants, and placed within an XRCT scanner. The container needed to be large enough such that the ants could comfortably tunnel within the domain, yet small enough to obtain detailed x-ray images of all the individual grains. Furthermore, the casing needed to be cylindrical shaped so that it situated within the scanner. A plastic frustum was chosen as the experimental container, which was 11.4 cm in height, 7 cm in minimum diameter and 9.8 cm in maximum diameter. A plastic top for the container was 3D printed, with a hole in the center for depositing the ants.

Soil and Ants. Quikrete soil of size 10/12 (1) was utilized for this experiment by passing store bought sand through a mesh size 10 (2 mm) followed by a mesh size 12 (1.7 mm) sieve, and keeping the grains which passed through only the former sieve. Later analysis revealed the sieved granular material’s average radius (maximum distance from centroid to surface) was 2.34 mm. Pogonomyrmex harvester ants were utilized for this experiment. Pogonomyrex ants were chosen because of their prolific digging and ability to handle grains on the mm scale, such as those used in the experiment that are ideal for XRCT imaging. Ants were ordered from antsalive.com.

Experimental Procedure. The goal of the experiments was to obtain the orientations and shape of each particle in the device as ants were digging. To achieve image resolution on the order of 0.1 mm, x-ray tomography was performed.

The soil sample was prepared by mixing 500 ml of 10-12 quikrete soil with 20 ml of water. This mix was poured into the plastic frustum. Multiple samples were created for the experiment. The number of grains amounted to around 60,000 grains each time. The sample was then placed into the x-ray tomographic scanner. An initial high resolution scan with voxel edge length 70µm was performed. Then, 15 ants were released at the top of the sample, and the plastic top was secured on. Following this, a half-resolution scan with voxel edge length 140µm (last 4 minutes) was taken every ten minutes over the course of 20 hours, thereby tracking the dynamic states of the sample. The lower resolution scans can discern particle details on the scale of 1/4 of the average particle diameter: enough information such that one can track the movement of all the particles imaged in the initial high resolution scan. Six experiments were performed overall, however due to the XRCT machine shutting off unintentionally over night, certain experiments were missing data points. Note this did not affect the quality of experiments which were measured.

The results of these scans were 3D tiff files, each corresponding to a particular experiment and time. These tiff files were then processed in the subsequent steps to obtain interparticle forces. From these images, the porosity φ could be determined via spam (2).

Image Processing. To obtain forces between grains, we created digital particle avatars which mimicked the morphology of particles in the sample. Each avatar is a 3d discrete level-set of the grain surface, along with a collection of coordinates on the particle surface. For a given particle, its level set representation is a scalar function defined over three dimensional space, where its value at a point is the signed distance from said point to the particle’s surface, see Fig. S1. Before processing, x-ray tiff images were adjusted for consistent orientation and lighting across time, and a watershed algorithm isolated the voxels corresponding to each grain in the high resolution scan. This analysis was performed via the python library spam (2).

The process of converting a tiff file into level set particles is detailed fully in (3). In summary, non-local means filtering is applied for denoising the watershed. Then, the level set of each individual grain is calculated through the process of re-initialization, as are its set of surface coordinates. Particle positions and rotations are also recorded.

To determine the frame at which grains disappear, the lower resolution XRCT images at different instances in time, or frames, were autonomously compared. For a low-resolution scan taken at a particular frame, if the mean gray value of the voxels that were occupied by a particle in the initial high resolution scan dropped below 128, the grain was labeled as removed and the step at which the particle disappeared was recorded.

Tunnel Morphology Analysis. To generate Fig. 2 in the text, a spline was fit to the initial positions of all particles that were removed for each of the experiments. To do so, k-means clustering was first utilized to isolate the centroids of the removed particles at each frame. The distances between centroids were computed to discern tunnels from one another. Then, a spline was fit to each set of centroids corresponding to a particular tunnel. The spline knots could be manually perturbed for a finer fit. Then, the spline was discretized into 300 points for further analysis.

Digging angle φ at a given point along the spline was determined by calculating the spline’s derivative, then finding 90 – the angle between this direction and the z axis. This measure was chosen because it was similar to the angle of repose for a sandpile (4). For further analysis, the shape of the tunnel cross section at each spline point was calculated as follows: a plane was fit at the spline point with its normal vector pointed in the direction of the spline derivative. The initial centroids of each removed particle about one grain diameter away from the plane were projected onto the plane to form a 2 dimensional ‘slice’. Next, a convex hull was calculated from the projection of the removed particle centroids in the 2d plane. The center of the convex hull was determined, and the average distance from the edge of the hull to the center was taken to be the tunnel radius at this spline point. To detect which particles were on the tunnel surface at a particular frame, all grains within approximately one grain diameter (2.8 mm) were classified as tunnel surface particles. Finally, principal component analysis was performed on the projected centroids in the plane, and the ratio of the largest to smallest eigenvalue was taken as the tunnel aspect ratio. All processing in this step was carried out by the SciPy Python library.
**LS-DEM Simulation.** Once the level sets and surface points of all the particles in the sample were obtained, the avatars could be used in simulation. As stated in the primary text, an extension of the DEM was used - the level set discrete element method (LS-DEM). In DEM, particles move according to classical rigid body mechanics. In the variant of interest here, particles may overlap each other. For each point on one particle which is overlapping another, a contact force is calculated. The normal force imparted from one particle onto another is a multiple of overlap distance, with constant of proportionality $k_n$. Shear force, perpendicular to normal force, is determined according to a Mohr-Coulomb failure criterion with coefficient of friction $\mu$ and stiffness $k_s$. While calculating the overlap distance is trivial for spheres, it can be difficult and computationally taxing for particles of arbitrary shape. By representing the particles as level set avatars as in LS-DEM, overlap calculations for oddly shaped particles were tractable and accurate. Wall interactions were handled through an analytical expression relating position to wall overlap. See (5) for details on LS-DEM.

Some particles, typically at the top and bottom of the container, were not imaged properly and their level set was non-physical. Thus, these avatars were removed before simulation. Other particles began with too high an overlap between each other, leading to high initial velocities in the simulation. This occurs usually due to errors in the image processing step. Such particles had their volume reduced by uniform contraction.

We use the calibration parameters similar to those in Kawamoto (6), which have been shown to predict the location and behavior of shear bands within digital twins of triaxial test. We take particle density to be 2650 kg/m$^3$. $k_n$ is the same as that in Kawamoto at $(3 \times 10^3)$, with a slightly reduced $k_s = 0.8k_n$. As demonstrated in (5), the specific value of $k_n$ does not have a significant effect on results. We take $\mu = 0.45$, which is similar to but slightly lower than Kawamoto, which consisted of rougher grains. Furthermore, Kawamoto demonstrates that in the low-strain regime, such as in our sample, the response of the system to perturbation is not very sensitive to the coefficient of friction. Global damping is set to $100$ s$^{-1}$, as it was found that this value led to efficient convergence to equilibrium, yet was large enough such that collapses and large displacements could still occur. The coefficient of restitution for local damping between grains is set to 0.4, to dampen spurious oscillations. Correctness was checked by following procedures in (7).

To include cohesion in the model, particle bonding was implemented according to (8). This model is equivalent to placing a beam between each pair of particles within a specified distance, which ruptures when the normal stress in the beam reaches a threshold $\sigma_c = \frac{|F_n|}{A} + \frac{M^r|R}{I} = \frac{C_n}{A}$ or the shear stress $\tau_s = \frac{|F_s|}{A} + \frac{|M^r|}{I} = \frac{C_s}{A}$, where $A$ is bond area, $C_n$ is the maximum bond force in the normal direction and $C_s$ is for shear, $F_n$ and $F_s$ are the normal and shear forces in the beam respectively, and $M^r$ and $M^s$ are the normal and shear moments respectively. We take the bond area $A = 1mm$ (referencing (9)), and $I$ and $J$ are the area and polar moments of inertia of the beam. The normal direction of a bond between two particles is given by the direction of the vector connecting the two closest points on the aforementioned grains. While typical liquid bond models in DEM do not provide shear or moment resistance, such models have been developed primarily for spheres (8). We find that adding shear and moment resistance is necessary for maintaining tunnel stability in all experiments. This is most likely due to the irregular shape of particles, and the more complicated geometry of cohesive bonds between grains. To validate our model, we perform angle of repose simulations along with experiments (see below). We also reproduce the DEM simulations from Santamarina et al, in which DEM particles are dropped through holes of increasing size in the flat bottom of computational silos - see figure 6 in (10). We successfully predict the regions of stability/instability in accordance with the experimental results in said paper.

This model was chosen as to minimize plastic contact breakage during simulation, such that the closest approximation of the force distribution in the imaged sample was obtained. The original bonding model was developed for spherical grains. Thus, we extended this formalism by calculating bond displacement from the two closest points between the participating grains at bond creation. The force needed to break bonds was calculated from equation (1) in (10):

$$C = \frac{\pi}{2} \sigma d (2 - \left(\frac{8}{9} \omega G_S\right)^{1/4})$$

with air-water surface surface tension $\sigma = 0.073 N/m$, water content $\omega = 0.03$, specific gravity $G_S = 2.65$ and particle diameter $d = 2.3 \text{ mm}$ resulting in cohesive strength $C = 0.378 \text{ mN}$. Note this formula applies to spherical particles. We initially assumed it was a sufficient approximation for non-spherical particles due to the local smoothness of grains at contacting points. Nonetheless, it was discovered that $C_n \geq 2 + C$ for tunnels to be stable in our simulations. This may be due to the assumption of sphericity in the bond strength formula. During simulation, every 10 timesteps a particle bond is created between any unbonded pair of grains which are within 0.28 mm of each other. The normal force needed to break bonds was set to $C_n = 2C$, and shear $C_s = 0.8C_n$. Normal bond stiffness was $k_n = 2C$, and $k_s = 0.8k_n$.

For the first frame of the simulation, an equilibrium step was conducted where particles settled from their starting configuration to a resting configuration. The simulation was run until the kinetic energy converged to a value less than $5kg \text{ vox}^2/s^2$. We also checked that the total force on each grain was sufficiently small, such that the simulation total energy was at a stationary point.

The following was then performed for each frame: first, the final configuration of the previous frame was used as the initial configuration for the current. Then, the particles removed between the current and previous image were deleted from the simulation. The new configuration was run to equilibrium, and the process was then repeated for all imaged frames.

**Angle of Repose.** There is no agreed upon definition of the angle of repose (AOR) for a granular material, nor is there a standardized method for determining the angle - particularly for cohesive grains. For practical purposes, we define it as the
steepest slope of the unconfined material, measured from the horizontal plane on which the material can be heaped without collapsing’ (4).
Fig. S1. Example of 4 particles used in LS-DEM simulation, obtained from XRCT. 0 isosurface of levelset given by purple mesh, with surface points superimposed.
Fig. S2. Distribution of particle volumes of grains removed by ants (Removed grains) and grains kept by ants (Kept grains) across all 3 experiments. The difference between the two distributions is statistically significant, with $p < 0.005$ under Kolmogorov-Smirnov test.
Fig. S3. LS-DEM pluviation simulation to find AOR. Particles were dropped through a filter into a conical pile (top left). Particle centroids were used to construct a 2D cross section (top right), which is centered at the origin and rotated through a circle (see movie S4). A convex hull is fit to the projection of centroids in each plane (black lines). In a given cross section, centroids used for estimating AOR were highlighted in green, with the red line denoting least squares fit. Bottom: rotation angle of projection plane vs. AOR of cross section.
Fig. S4. Experiment 1 tunnel 1
Fig. S5. Experiment 2 tunnel 1
Fig. S6. Experiment 2 tunnel 2
Fig. S7. Experiment 3 tunnel 1
Fig. S8. Experiment 3 tunnel 2
Movie S1. Grains with contact forces during each stage of excavation throughout the tunnel in experiment 1. Each image in the video corresponds to one of the ordered points along the tunnel axis starting from container top, obtained from black spline in Fig. 1. Number at the bottom indicates corresponding spline point. For a given image, the cross section of the tunnel at the corresponding spline point is pictured for 8 x-ray scans, ordered in time chronologically. Time increases from left to right, with the top row preceding the bottom row. Branch vectors are displayed, with line thickness indicating magnitude of force acting on the grains involved. Yellow denotes particle that will be removed by the ants before the subsequent scan.

Movie S2. Video of experiment 1. On left, each image corresponds to a particular x-ray scan, or frame. Digital avatars of imaged grains on the tunnel surface are rendered. Blue grains indicate particles that will be removed by ants before the subsequent frame. On the right is the corresponding forces in tunnel surface grains for each frame, obtained from LS-DEM simulations.

Movie S3. An ‘ant’s view’ of the green tunnel in experiment 2, i.e. what an ant would see when traversing the finished tunnel. This visualization was obtained by rendering the particle avatars with the correct position and rotation, as obtained from XRCT. Then, images were taken of the rendering along the interpolating spline, with viewing angle given by the spline’s gradient.

Movie S4. Video of algorithm used to estimate angle of repose of a 3d sand pile from particle centroids. Pictured is the location of particle centroids projected onto a plane with normal horizontal to gravity and located at the pile center. Each frame of the video corresponds to the plane rotated at a specific angle about the z axis, see SI text and Fig. S3.

References