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REVIEW PAPER

Geotechnical insights of mammal burrows in loose desert sand

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Abstract
Loose desert sand poses a constraint for geotechnical engineers to construct tunnels without a lining, which is typically steel, concrete, or slurry shield. Many desert mammals, however, can construct tunnels in loose sand, and the tunnels can remain stable over extended periods of time in harsh desert environments. This study presents the state of knowledge on mammal burrows in loose desert sand and provides insights from a geotechnical engineering perspective with the aim of understanding how desert mammals tackle a geotechnical challenge. The study presents these desert mammals as bio-geotechnical engineers and explains their burrow stability using three fundamental soil mechanics principles: (i) unsaturated soil mechanics, (ii) compaction, and (iii) soil cementation. Damara mole-rats, kangaroo rats, pocket gophers, and round-tailed ground squirrels are presented as the desert biogeotechnical engineers. Proof-of-concept experiments conducted with a poorly graded fine sand demonstrate the effects of the fundamental soil mechanics principles used by the animals on soil strength. A limit equilibrium tunnel stability analysis performed using sand from a kangaroo rat habitat in the Sonoran Desert also demonstrated the link between tunnel stability of desert mammals and the three geotechnical principles.

Keywords Damara mole-rat · Kangaroo rat · Pocket gopher · Round-tailed ground squirrel · Shallow tunnels

1 Introduction

Tunnel construction in loose sand is a challenge without a lining, especially for shallow tunnels, because the stand-up time is very short in loose sand [11]. Therefore, tunnel stability during and after construction is maintained, and surface settlements are controlled by permanent linings [56, 62]. Tunnel face stability during excavation is a major concern when tunneling in sand, so the tunnel face is supported during excavation typically with a slurry shield or earth pressure balance tunnel boring machine to control ground deformations and prevent face collapse [1, 6, 22]. The internal pressures generated by the liner support the cutting face against the existing overburden and hydrostatic pressures, limit plastic deformations in the sand, and therefore prevent face failure or collapse of the tunnel [6]. The type of the lining may vary depending on the tunneling approach but is broadly classified as segmental (precast concrete or cast iron) or sprayed (concrete or bentonite slurry).

Only humans use concrete, steel linings, or slurry shields to construct tunnels. Desert animals construct tunnels without such materials. For animals, tunneling is a subset of behaviors associated with burrowing and an adaptive form of digging. Burrows first appear in the fossil record during the Carboniferous period (385.9–298.9 mya), signifying the importance of burrows to terrestrial animals [44]. Burrows are defined as having both tunnels and chambers, which are specialized designs according to function (Fig. 1). Each tunnel has its own separate function such as escaping, food storage, nesting, or sometimes defecation. The geometry of the tunnels changes based on function. Burrows are refugia from abiotic and biotic constraints [19, 68]. Animals spend much of their lives in burrows, leaving to forage, mate search, and for dispersal [58]. The burrows are constraint-breaking adaptations that

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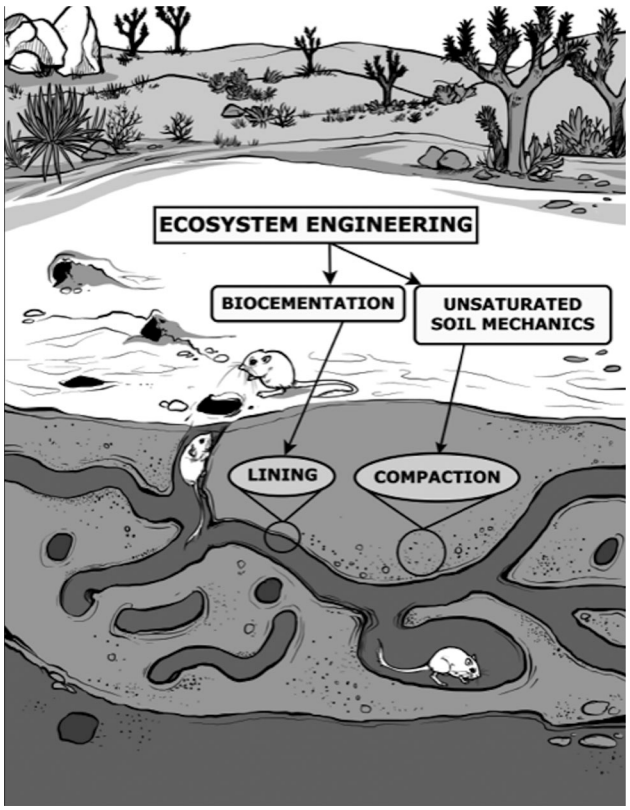

Fig. 1 A conceptual model depicting a kangaroo rat (*Dipodomys sp.*) burrow to illustrate the principles of bioinspired geotechnical engineering explored in this paper. Desert rodents are ecosystem engineers that build burrows and tunnels that vary in size in shape in response to function and constraints of the environment. Animals may overcome these constraints via biocementation, compaction, and unsaturated soil mechanics principles

lead to increased survivorship and livelihood in otherwise inhospitable environments.

Especially in desert conditions, the survival of burrowing animals depends on burrow stability because food and water resources are limited relative to other habitats, environmental stochasticity can be extreme, and deserts lack vegetation and other features for refuge [44]. Deserts are harsh environments with extreme daily and yearly temperature fluctuations. For example, in the Great Basin Desert, the average temperature in January is − 2 °C, while summer temperatures can rise as high as 57 °C [45]. Daily temperature fluctuations can be as high as 40–50 °C [46]. Relative humidity (RH) can drop to as low as 5% and can rise over 90% during a day or a year [24, 46, 74]. In addition, local convective, or high-intensity, storms are common in desert environments, especially in the summer and fall months, and can raise the soil saturation rapidly [12, 46]. The mechanical and hydraulic behavior of desert soil also poses unique constraints on desert animals. Loose desert sand has low strength, limited water retention, and high hydraulic conductivity. Therefore, tunneling in loose desert sand and keeping the tunnels stable and dry during storms are challenging.

Burrows are crucial for the survival of burrowing desert animals, who have evolved to construct burrows in the desert sand, maintain the stability of burrows over their lifetime, and make them resilient to extreme environmental conditions [44]. Desert mammals evolved to overcome a geotechnical engineering challenge—constructing stable tunnels in loose sand. Our study aims to present the state of knowledge on the mammal burrows in loose desert sand and provides insights from a geotechnical engineering perspective to understand how desert mammals tackle a geotechnical challenge. This review presents an integrative overview of desert mammal geotechnical feats burrowing in desert sand, describes geotechnical engineering principles to biologists, and posits that new insights will be gained by synthesizing these disciplines. The paper explains the stability of burrows using three fundamental geotechnical engineering principles (or combination of them): (i) unsaturated soil mechanics, (ii) compaction, and (iii) soil cementation. The potential effects of burrowing habits of the animals, burrow microclimates, and burrow microbial activity are conceptually linked to improved soil strength and corresponding burrow stability through controlled laboratory experiments conducted with a poorly graded fine sand. A limit equilibrium tunnel stability analysis also demonstrated the link between the three geotechnical engineering principles and tunnel stability. Methods are recommended on how geotechnical engineers can help ecologists understand the evolution of burrows.

2 Burrowing desert mammals and burrow structures

Burrow entrances, tunnel size and diameter, and complexity depend on multiple factors including body size, sociality, and the mechanics of local soil. Mathematical modeling by Carotenuto et al. indicates that the more compact soil is, the smaller the mammal must be to effectively tunnel [61]. Conversely, larger animals have greater mass-specific metabolic rates and thus are restricted to above-ground environments due to low oxygen circulation below ground [80]. The "cost-of-burrowing" hypothesis posits that burrowing places energetic costs on fossorial and semi-fossorial animals. However, reduced basal metabolic rate compensates for these costs [33, 76]. In addition, desert mammals exhibit extremely low food requirements given their body sizes because taking refuge in a burrow reduces thermoregulatory and metabolic costs [53]. They can thrive in harsh desert environments. Thus, burrowing through the physical constraints of soil is a constraint-breaking adaptation.

In a given soil profile and among burrowing mammals, solitary fossorial species construct larger nest chambers compared to semi-fossorial and colonial species despite similarly sized tunnel openings [55, 77]. Such larger chambers could house more nest material, aiding in thermoregulation for single individuals. Social and colonial mammals build more complex burrows because of the varied activities associated with communal life [55]. Humans build the largest tunnels compared to their body size (Fig. 2). However, human tunneling methods use machinery and construction materials such as concrete and steel. Therefore, the biological burrowing principles discussed below do not yet directly translate to human tunnels.

The burrowing desert mammals investigated in this paper are kangaroo rats, pocket gophers, round-tailed ground squirrels, and Damara mole-rats. The burrow structure of these animals all consists of tunnels and chambers, but the diameter of burrow entrances varies (Fig. 2 and Table 1). The animal body masses also vary between 78 to 120 g (kangaroo rat, [17]) and 165 to 254 g (pocket gophers, [79]). While body length and other morphometric dimensions likely affect burrow tortuosity and other architectural considerations, body mass is the most repeatable small mammal measurement and thus the focus of this study.

Table 1 Body masses of the desert mammals reviewed in this study and the entrance diameter of their burrows

Animal	Body mass (g)	Mean burrow entrance diameter, D (cm)	Region	References
Kangaroo rat	78–120	12.1	Sonoran Desert	[17, 73]
Damara mole-rat	90–198	6.4	Kalahari Desert	[14, 49]
Pocket gopher	165–254	7.6	Southwestern NM and Western TX	[20, 79]
Round-tail ground squirrel	110–170	5.7	Death Valley National Monument	[29, 30]

2.1 Damara mole-rats

Damara mole-rats (*Cryptomys damarensis*) live in sand dunes consisting of noncalcareous red sands of the Kalahari Desert and construct their burrows only when the soil is unsaturated. The animals avoid loose dune crests and excavate their tunnels on the more compacted slopes or valleys of the sand dunes [26, 49]. The Damara mole-rats live in their sealed burrow systems in colonies with a group size of up to 40 individuals, spending most of their lives in the burrows where they perform most of their ecological tasks including foraging [15, 39]. The burrow systems include a long (up to 130 m) primary flat tunnel at less than 40 cm depth, with shallow and deep secondary tunnels [49, 69]. The shallow secondary tunnels are less than 20 cm deep and used as foraging burrows, whereas the deep secondary tunnels branch out from the primary tunnel at steep angles (23°), go into the nests and food storage areas, and are as deep as 2.5–3.5 m [15, 49]. There is evidence that the shallow secondary tunnels collapse from time to time, and the mole-rats either repair these tunnels or block their access from the primary tunnel [49].

After construction, the tunnels at 25–29 cm were found to withstand the temporary surcharge from human and

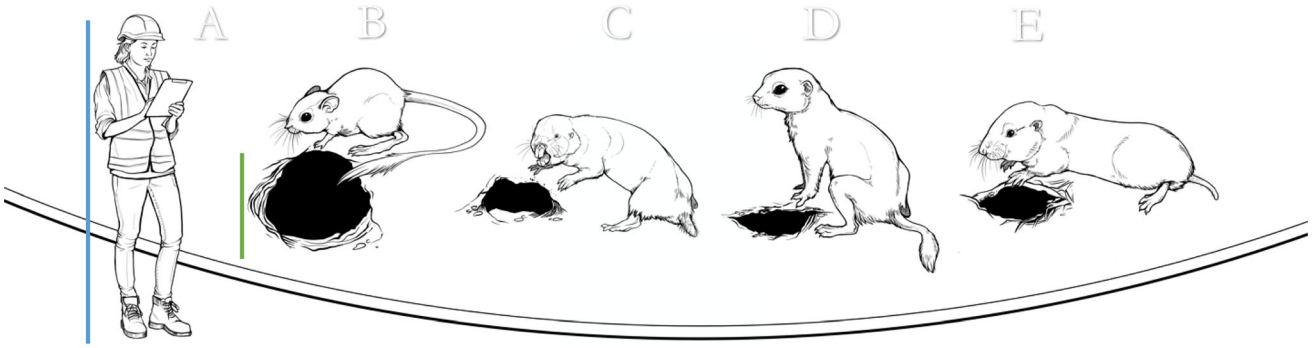

Fig. 2 A human and the four focal animals of this review depicted near their burrow entrances: **A** Human (*Homo sapiens*) and a double-lined arc representing the tunnel diameter of a subway line, **B** kangaroo rat (*Dipodomys sp.*), **C** Damara mole-rat (*Fukomys damarensis*), **D** round-tailed ground squirrel (*Xerospermophilus tereticaudus*), **E** pocket gopher (*Geomys arenarius*). The blue line next to the human and subway line is approximately 156 cm. The green line next to the kangaroo rat is 12 cm. The human and subway tunnel were congruently scaled down to better enable comparison across species

from an off-road vehicle [49]. However, burrows often collapse after a flood event, and Damara mole-rats start the construction of their new burrows immediately after [34]. The need for burrowing in a short time span after the rainfall is suggested as the reason why Damara mole-rats need the workforce of multiple individuals and therefore live in colonies [40, 71].

2.2 Pocket gophers

Pocket gophers (*Geomys arenarius*) are fossorial mammals in the family *Geomyidae*. [52]. This species dig their burrows in loose soil such as disturbed terrain or sandy areas [79]. Approximately 80% by volume of a burrow is a shallow network of feeding tunnels connected to a deeper, central, and more permanent system of chambers used for nesting, food storage, sanitation, and retreat [54]. Pocket gopher mounds are short-lived (i.e., 1–3 years), indicating that these animals do not occupy the same burrow for extended periods of time [78]. Burrows may reach a maximum depth of 1.8 m with a mean diameter of 7.6 cm that varies with body mass [20].

2.3 Round-tailed ground squirrels

Round-tailed ground squirrels (*Xerospermophilus tereticaudus*) live in sand dunes of the small portion of Saratoga Springs, in the extreme southern portion of Death Valley National Monument [18]. The burrows in fine sand can be 25 to 50 cm deep [41]. Burrows may have multiple entrances and have narrow tunnels, with an average diameter of 5.7 cm. Active burrows are plugged at about 45 cm depth with 2 to 4 entrances [29, 30]. The burrowing behavior of round-tailed ground squirrels shows evidence of compaction during construction as these animals show "violent shaking motions" of the entire body after an increment of excavation [29]. Given the limited information on the biomechanics of tunneling, we recommend biomechanists collaborate with geotechnical engineers to study the intensity, amplitude, and propagation of the waves from the shaking motion to understand how such intense motions can shape tunnel systems.

2.4 Kangaroo rats

Kangaroo rats (genus *Dipodomys)*, of the deserts of North America, are keystone desert rodents that are known for their well-developed burrow systems in which they live and store food [7, 59]. It may take up to two years for kangaroo rats to construct their elaborate burrows [16]. After construction, kangaroo rats occupy the same burrow for many years. Young kangaroo rats of some species are known to inherit their burrows from their parents [42]. Kangaroo rats actively maintain the stability of their burrows, which eventually collapse after abandonment [37]. Some species of kangaroo rat (e.g., *D. spectabilis*) burrow in loose sand dunes in the Sonoran Desert. These burrows are hotspots for soil microbial activity, and the ceilings of the burrows are covered with soil biocrust [35, 36]. The conditions in *D. spectabilis* burrows were found to be ideal for fungal growth and mycotoxin production [59].

Compared to many desert denizens, kangaroo rat burrow is tortuous and labyrinth. A mound may have up to 16 entrances ranging from 12 to 16 cm in diameter. Burrow tunnels rise and fall relative to Earth's surface and many intermingle with one another while others are dead ends. The tunnels vary in size and shape. Some are nests for young, which have been found 11 m beyond the main tunnel entrance. Food stores are found centrally located at depths from 15 to 57 cm, in chambers ranging 15 to 25 cm in diameter. Other tunnels averaged 8 cm in height and 11 cm in width [73]. Yet, much of this information is derived from a century-old study. New insights could be derived if the 3D and tortuous architecture of kangaroo rat burrows could be nondestructively mapped and sampled.

3 Tunnel Stability Analysis

The tunnel stability of animal tunnels was evaluated using an upper-bound limit equilibrium analysis that uses the limit theorems of plasticity [27]. The upper bound (i.e., unsafe stress level) is the selection of a kinematically possible collapse mechanism together with an appropriate work rate calculation, in which case the external loads must cause a collapse [11]. The appropriate work rate calculation involves self-weight of the soil and corresponding tunnel pressure [11]. The possible collapse mechanisms and the detailed calculations can be found in [11] and [27]. According to the limit equilibrium analysis, the stability of burrows can be evaluated assuming an equivalent continuum with strength estimated from the net interparticle attractive force [31]. According to the equivalent continuum, the upper-bound limit equilibrium analysis for 2-D planar failure is described by Eq. 1 [31].

$$\frac{A}{W} = \frac{6}{\pi}(1-n)\frac{D}{d_{50}} \tag{1}$$

where A is the minimum net attractive force required for tunnel stability, W is the self-weight of the unit volume of soil, n is porosity, D is tunnel diameter, and d_{50} is the average particle size.

The net attractive force is a combination of attractive van der Waals forces, attractive capillary forces, and repulsive double-layer forces. The repulsive double-layer force is not considered in this study because the magnitude

of double-layer force in sands is negligible compared to the remaining forces [47]. The van der Waals force is defined as [64]:

$$VDW = \frac{A_h}{6t^2}\frac{R_1 R_2}{R_1 + R_2} \quad (2)$$

where A_h is the Hamaker constant, t is the particle separation distance, and R is the radius of the spheres. Hamaker constant was taken as 0.64×10^{-20} J (silica-water–silica) for a saturated soil environment and 6.5×10^{-20} J (silica-free space-silica) for dry soil environment [38, 63].

Tunnel stability analysis was conducted for an idealized soil with uniform spherical particles, in simple cubic (SC) packing and tetrahedral (TH) packing to represent the loose and dense conditions. According to the packing scenarios, one atom can fit in the SC unit cell, and four atoms can fit in the TH unit cell. Unit volumes for SC and TH packing have void ratios of 0.91 and 0.34. For coarse-grained soils with monosized particles, the material properties, water retention, and suction stress of real soil are presumed to range in between these two idealized packing cases [50].

Capillary force (C) for SC packing is a function of water content w and air–water surface tension T_s = 0.072 N/m at 25 °C and is defined as Eq. 3 for water content less than 0.06 [64].

$$C = \pi T_s R\left[2 - \left(\frac{8}{9} w G_s\right)^{\frac{1}{4}}\right] \quad (3)$$

where G_s is the specific gravity.

For the stability analysis of animal tunnels, a poorly graded desert sand from a kangaroo rat habitat in the Sonoran Desert was selected as the model soil. The soil was characterized following the standard methods ASTM D6913 [10] for particle size distribution (Fig. 3) and ASTM D854 [8] for specific gravity (2.67). The void ratio for this subrounded sand ranges between approximately 0.4 and 0.8 [81].

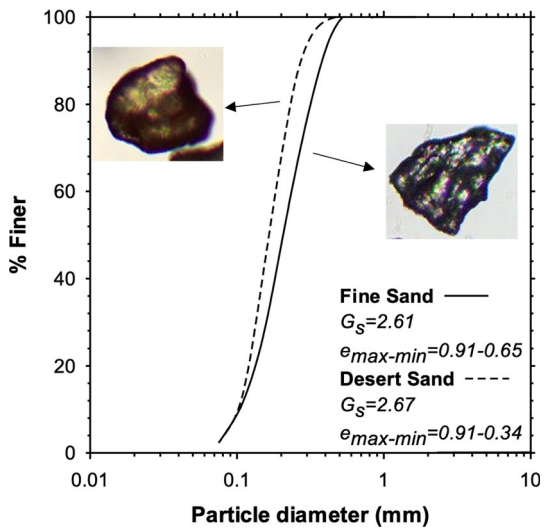

Fig. 3 Particle size distribution curve of sands

The net attractive force normalized by weight (A/W ratio) was determined from the upper-bound limit equilibrium analysis (Eq. 1) for both SC packing and TH packing (Fig. 4). The mean particle diameter (d_{50}) was taken as 0.16 mm according to the soil from the kangaroo rat habitat in the Sonoran Desert. The A/W ratio for SC packing was found as 756 for kangaroo rats, 400 for Damara mole-rats, 475 for pocket gophers, and 356 for round-tailed ground squirrels.

Van der Waals forces were calculated for both particle–particle and particle-water-particle configurations as described in [47]. However, because of the small variation in weight-normalized van der Waals force in SC packing between dry (1.9) and saturated (0.2) state compared to weight-normalized capillary force (up to 530), the normalized van der Waals force was taken as a constant of 1.9 in the entire saturation range. This was done to determine the minimum capillary force required for stability. Therefore, considering the van der Waals force as a constant, the limiting degree of saturation that provides the limit A/W ratio for each animal tunnel was calculated based on the

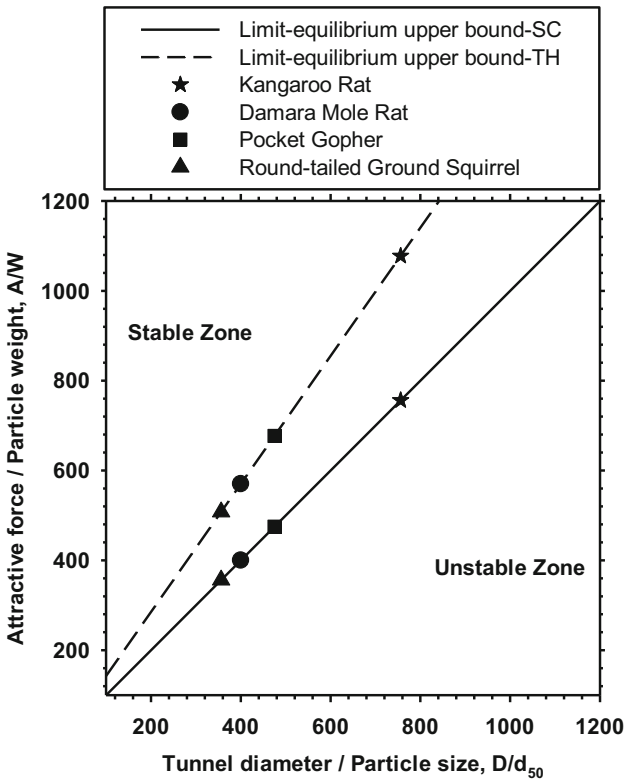

Fig. 4 Limit equilibrium analysis results for the Kangaroo rat, Damara mole-rat, Pocket Gopher, and Round-tailed ground squirrel both simple cubic (loosest possible condition) and tetrahedral packing (densest possible condition)

trends in capillary force normalized with weight (Fig. 5). The limiting degree of saturation was calculated as 0.40 for Damara mole-rats, 0.09 for pocket gophers, and 0.79 for round-tailed ground squirrels. However, considering that the capillarity equation does not include (i) cavitation, (ii) the pendular regime of the soil water retention curve, and (iii) flattened particle contacts [21], the limiting pressure is likely less than 0.79 for round-tailed ground squirrels, less than 0.40 for Damara mole-rats, and higher than 0.09 for pocket gophers. The expected actual behavior is semi-quantitatively shown with gray lines in Fig. 5 based on previous studies [4, 5, 51], which argue that the capillary force should be zero at $S = 0$ and $S = 1$, because of a lack of an air–water interface. The difference in limiting saturation is demonstrated for Damara mole-rats in Fig. 5 with arrows for SC packing. The limiting A/W value was calculated from the upper-bound limit equilibrium analysis as 400. When the maximum normalized van der Waals force ratio (1.9) was subtracted from this value, the limiting saturation that corresponds to the minimum C/W of 398.1 was calculated as approximately 0.35 on the gray line (expected actual behavior), compared to 0.40 on the black line (calculated from Eq. 3).

Based on this analysis, kangaroo rat burrows cannot stay stable under any saturation value in simple cubic packing, indicating mechanisms other than van der Waals attraction and capillarity are responsible for the stability of kangaroo rat burrows.

If the animal tunnels are in dense sand, such as in tetrahedral packing, the limit A/W ratio is 1080 for kangaroo rats, 570 for Damara mole-rats, 680 for pocket gophers, and 510 for round-tailed ground squirrels (Fig. 4). A similar analysis was performed to calculate limiting saturation based on the semiquantitative trend in capillary forces. The capillary force for TH packing that was calculated according to [21] is shown in Fig. 5 with dashed lines. Accordingly, the limiting degree of saturation was calculated as approximately 0.1 for pocket gophers, while for Damara mole-rats and round-tailed ground squirrels, the limiting saturation analysis indicates that tunnels should be stable at any degree of saturation greater than ~ 0.05. However, for kangaroo rats, this suggests that burrows should not be stable at any degree of saturation if van der Waals attraction and capillarity are the only two mechanisms that contribute to tunnel stability. An additional potential mechanism, cementation, is discussed in the next section. However, additional contributing mechanisms not reviewed in this paper are possible.

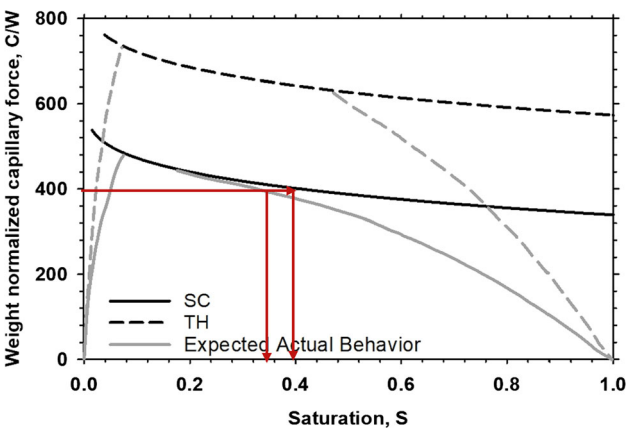

Fig. 5 Tunnel stability analysis for simple cubic packing (loose) and tetrahedral packing (dense)

4 Geotechnical engineering principles used by burrowing desert animals

The stability of tunnels was explained using three fundamental geotechnical engineering principles: (i) unsaturated soil mechanics, (ii) compaction, and (iii) cementation. The effects can be observed individually, or multiple effects may be combined. For example, compaction effects can be observed individually, where loose soil at a certain degree of saturation (S) has lower strength than dense soil at the same S. The combined effects of unsaturated soil mechanics and compaction is observed when soil compacted at optimum has higher strength than soil compacted at dry or wet of optimum. This section first presents the individual effects and then the combined effects are discussed through proof-of-concept experiments.

4.1 Proof-of-concept experiments

Proof-of-concept experiments were conducted using a poorly graded fine angular sand (Fig. 2). The specific gravity of the sand was measured according to ASTM D854 [8] as 2.61. The maximum and minimum void ratios were measured according to ASTM D4254 [9] as 0.91 and 0.65.

A purified xanthan gum (Sigma-Aldrich, CAS 11138-66-2) was used to replicate biocementation. Among many biocementing agents, xanthan gum was selected as the model cementing agent to replicate cementation in desert biocrust. Desert biocrust is a complex ecosystem that includes microorganisms such as cyanobacterial, green algal, and fungal species [13]. In biocrusts, soil particles are cemented by biofilms and biofilaments [57]. Biofilms and biofilaments are porous materials [48]. Water retention in the pores of biofilms was shown to influence the mechanical behavior of sand–biofilm composite [66]. Xanthan gum is a commercial biopolymer, which is a processed form of biofilm, where the extracellular polymer (EPS) is separated from the bacteria and pulverized after

extraction. Therefore, xanthan gum was selected as a simple polymeric agent that shows water retention in its pores to replicate biocementation in the biocrust. Additional microbial communities and cementing agents may exist in animal burrows that are not represented by the polymeric cementing agent used in this study.

Dry sand was first mixed with 1% xanthan gum (by dry mass), and deionized water was added to bring the soil saturation to 60%. 1% was selected after preliminary experiments to replicate light cementation that is experienced in the field even at high saturations. Disk-shaped specimens were compacted using a custom-made mold described in Akin and Likos [2]. The specimens were dried to different saturations between 0.6 and 0.02, and tensile strength was measured using a small-scale Brazilian tensile strength (BTS) test as described by Akin and Likos [3].

The soil-water retention curve (SWRC) of the sand was measured using the transient release and imbibition method (TRIM) system [75]. TRIM uses the axis translation method to measure the transient outflow response of soil after exposed to a large change in suction. Dry sand was placed in a flow cell on a high air entry (HAE) ceramic disk and saturated from bottom to top. First, a drying test was performed by applying a sudden 3 kPa increase in suction, followed by 200 kPa increase. The outflow due to the increase in suction was measured over time using an electronic balance. The transient outflow response was used as an input in a numerical model that solves Richard's equation [60]. The solution of the inverse modeling gave SWRC. The van Genuchten fitting parameters (S_r, α, n *and* m) [32] were calculated by the interface graphic software. Using the fitting parameters in the van Genuchten model [32], $\left(S_e = \frac{S-S_r}{1-S_r} = \left[\frac{1}{1+(\alpha\psi)^n}\right]^m\right)$, the SWRC of the sand was generated.

4.2 Unsaturated soil mechanics

The strength of soils depends on the degree of saturation (or chemical potential of soil pore water), and this dependency can be quantified using the suction stress concept, which is the sum of net attractive force defined in Eq. 1 and cementation [51]. Using the suction stress as a single additional parameter, an effective stress equation can be formulated as [51]:

$$\sigma' = (\sigma - u_a) - \sigma^s \tag{4}$$

where σ is the total stress, σ' is effective stress, u_a is air pressure, and σ^s is suction stress. Suction stress is a function of saturation, and the function is referred to as the suction stress characteristic curve (SSCC). Equations 2 and 3 show the trends in van der Waals and capillary forces. The cementation component of SSCC is traditionally taken as a constant and unchanged with saturation [51]. However, Shariq et al. [66] recently showed that when the cementing agent is also porous or changes its physical properties upon wetting, such as polymeric materials, the cementation component of suction stress also depends on saturation.

In shallow depths, such as the ones involved in animal burrows, the contribution of suction stress on effective stress is critical. Figure 6 presents representative SSCCs for (a) uncemented clean sand and (b) clean sand cemented with a polymeric material. The SSCCs for the clean sand is calculated using the Akin and Likos model [4], and the SSCC for the cemented sand is from Shariq et al. [66].

For clean sand, only capillarity is present, which is zero at dry and saturated states and peaks somewhere in between, indicating that if a burrow is constructed in clean sand, it will have highest likelihood of survival when the soil saturation is between 0 and 1, which for the sand in Fig. 6a is around 0.8 S. This point will be called favorable saturation. When the sand is cemented with a polymeric material such as the biofilm in Fig. 6b, the favorable saturation is zero, where the maximum suction stress is obtained. The favorable saturation depends on pore size distribution, which for sand controlled by particle size distribution and packing.

The burrows of Damara mole-rats collapsing after a flood event and the construction of new burrows starting immediately after are parallel with the suction stress reducing to zero when soil becomes saturated, such as during the flood event, but reaching to a maximum immediately after the flood event as water infiltrates or evaporates and saturation decreases below 1 (Fig. 6a).

4.3 Compaction

Compaction is one of the oldest soil improvement techniques. From a biological perspective, soil compaction by animals is widely investigated as part of the efforts to understand biopedturbations and related changes in soil composition and nutrient availability [23, 78]. It is well-known in both geotechnical engineering and biology that compaction increases soil strength. A decrease in void ratio from 0.65 to 0.91 can result in 50% increase in shear strength in a poorly graded fine sand.

Soil compaction is an interesting problem in the science of burrows. An increase in the degree of compaction prepares soil for tunneling and allows more stable tunnels. Despite the seemingly salient effects of soil compaction on burrow construction and stability, little evidence was found of direct measurement. Many burrowing desert mammals take advantage of compaction either by (i) burrowing only in compacted slopes or valleys of sand dunes or (ii) compacting the soil during the excavation of the tunnels.

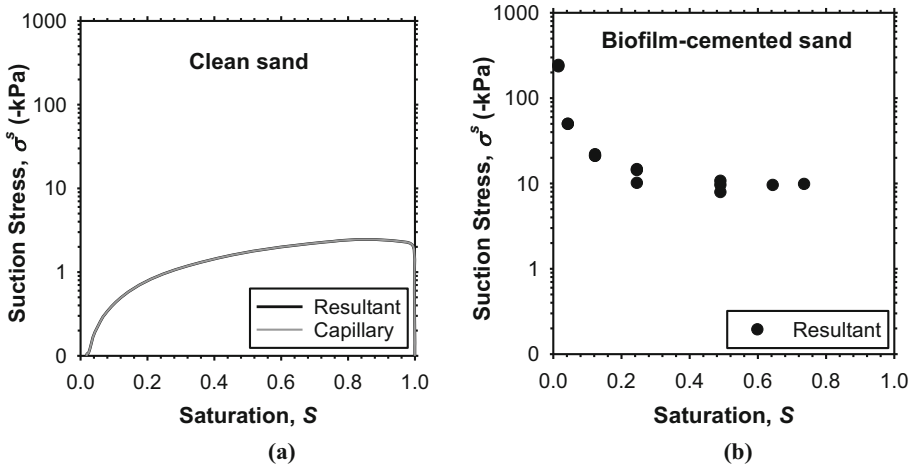

Fig. 6 SSCC of **a** uncemented clean sand (resultant and capillary overlap) and **b** clean sand cemented with a polymeric material

Compaction also has disadvantages for burrowing animals because an increase in the degree of compaction reduces tunnelling efficiency. The energetic cost of burrowing can be up to 9.5 times more in compact versus loose soils [70]. Desert mammals either avoid tunneling in compacted soil or employ multiple biomechanical solutions to tunneling through soils varying in the degree of compaction. For example, pocket gophers change their digging method depending on soil compaction. While expending more energy to tunnel with less oxygen, pocket gophers switch from scratch-digging with their forelimbs to chisel-tooth digging with their mouths [25]. Biomechanically switching from forelimb motions that shear soil from the compacted volume to chisel-tooth biting indicates the need for more force and pressure to break through increasingly compacted soil.

Tunnel stability analysis indicated that the burrows of Damara mole-rats and round-tailed ground squirrels should be stable regardless of changes in the degree of saturation in TH packing. However, likely because of increased cost of burrowing with compaction, animals do not burrow in dense sand and instead prefer waiting for wet periods to construct their burrows and take advantage of capillary forces.

4.4 Cementation

The sources of cementation in tunnel soils may include that of presence of organics, mineral precipitation, or biocementation. Even though no evidence was found on cementation due to organics or minerals exclusively in loose desert soil burrows, decomposition of animal bones, urine, animal feces, animal tissue, stored food, or nest material are potential sources for organics and minerals in burrow soils [78].

The limit equilibrium tunnel stability analysis showed that kangaroo rat burrows should not stay stable even in a dense state if capillary and adsorptive forces are the only attractive forces that contribute to tunnel stability. This suggests that an additional attractive force is necessary to keep the tunnels stable. Biocementation may be the source of the additional attractive force. If the microbial activity in the burrows results in biocementation, tunnel stability is improved. This is observed for the biofilm-cemented fine sand shown in Fig. 6b.

4.5 Combined Effects

The three above-mentioned principles are most often not observed individually. Rather, a combination of more than one factors is suggested to contribute to tunnel stability. For example, Damara mole-rats are found to excavate only when the soil is unsaturated. However, the contribution of suction stress to soil strength may not be the only factor. During dry seasons, desert sand is often referred as "hard" by biologists, and the energy cost is high for Damara mole-rats to dig burrows [67]. For an uncemented sand, suction stress is expected to be zero at dry condition, which would not result in "hard" soil, indicating the presence of desert biocrust (i.e., biocemented soil) on the surface.

To demonstrate this effect, BTS of biopolymer-enhanced sand at different concentrations was measured. Suction stress was calculated from BTS as described in Akin and Likos [3] and compared with the SSCC of uncemented sand (Fig. 7). Even 1% biopolymer resulted in approximately 10 kPa increase in suction stress over a wide range of saturations. However, the most prominent

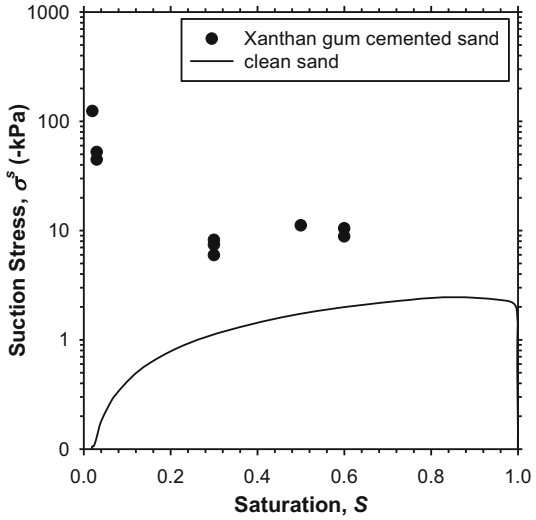

Fig. 7 Suction stress of xanthan gum-treated sand and untreated sand

increase was seen in dry condition, which is often the case in deserts. The suction stress of xanthan gum improved sand was 124 kPa, compared to 0 kPa suction stress of untreated sand.

5 Microclimates in the burrows and potential implications to tunnel stability

Burrows are adaptations to stochastic, harsh conditions in desert environments. As such, internal burrow microclimates differ from the external environment. Internal microclimates are subject to environmental fluctuations, especially near the surface. Environmental conditions (i.e., temperature and relative humidity) in the burrows are governed by burrow size, shape, and depth [19, 28, 43]. For example, relative humidity (RH) in the burrows varies daily, seasonally, and yearly in open burrow systems [19]. RH in round-tailed ground squirrels were found to vary between 24% and 90% over one week [72]. Similarly, for kangaroo rats RH was measured as low as 30%, but the RH can rise to 100% if the tunnel is plugged due to moisture content of the soil and animal metabolic activity [43, 65]. Although no direct evidence was found, a prolonged high RH environment in the burrows would prevent the soil from drying out, which results in higher suction stresses in burrow soil (Fig. 6) and correspondingly higher tunnel stability. The higher RH in closed burrows may also be a contributing factor to why Damara mole-rats prefer closed burrow systems. Sealing the burrows help maintain higher relative humidity (or higher chemical potential) in the burrows, which slows down (or prevents) soil drying, maintaining soil stay close to favorable saturation longer.

6 Conclusions

This study aimed to present the state of knowledge on mammal tunnels in loose desert sand and understand how burrowing desert mammals can overcome the geotechnical challenges of tunneling in loose sand without using a tunnel lining that is made of a construction material. An upper-bound limit equilibrium analysis demonstrated the necessary attractive forces for animal tunnels to stay stable in SC and TH packing and showed that kangaroo rat tunnels should not stay stable at any degree of saturation if van der Waals, and capillary forces are the only attractive forces that contribute to tunnel stability. Three fundamental geotechnical engineering principles (unsaturated soil mechanics, compaction, and cementation) were used to explain the stability of mammal tunnels in loose desert sand. The burrowing behavior of Damara mole-rats, who construct burrows only after a rain event, and only on more compacted slopes or valleys of sand dunes was linked to the increased suction stress with an increase in the degree of saturation and increased shear strength of the compacted soil. The negative effects of compaction on burrowing mammals were also discussed in relation to reduced tunneling efficiency. The adaptations that pocket gophers make in their digging behavior were linked to the need to improve tunneling efficiency in compacted soils. The elevated microbial activity in kangaroo rat burrows was linked to improved burrow stability through biocementation. The effect of soil microclimates on suction stress and burrow stability was discussed.

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Data availability The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Conflict of interest The authors have no competing interests to declare that are relevant to the content of this article.

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