A simple theoretical approach to the thermal expansion mechanism of salt weathering

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The traditional plate theory in solid mechanics is used to estimate the thermal stress caused by a superficial salt layer on a rock substrate. This preliminary investigation theoretically demonstrates that the thermal expansion of superficial salt layers is difficult to result in rock breakdown during the process of salt weathering.

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Weathering is essential to the landscape development in arid environments (Cooke and Warren, 1973; Laity, 2008; Smith, 2009; Viles, 2011; Goudie, 2013), mostly because this natural phenomenon can produce substantive clasts and fascinating landforms over long time periods. In the long history of weathering research (Turkington and Paradise, 2005; Goudie, 2013), various processes resulting in rock breakdown, e.g. insolation weathering, frost weathering, salt weathering, and biological weathering etc., were proposed and frequently investigated (McGreevy, 1982; Jenkins and Smith, 1990; Chen et al., 2000; Doehne, 2002). Salt weathering often occurs in desert and coastal environments. Three well-recognized mechanisms involved in this process are crystallization, hydration, and thermal expansion (Cooke and Smalley, 1968; Laity, 2008). It is obvious that salt weathering is principally controlled by rock strength and state of stress. The stresses generated by crystallization and hydration in porous materials can be quantitatively evaluated (Rodriguez-Navarro and Doehne, 1999; Scherer, 1999; Charola, 2000; Doehne, 2002), whereas analogous expressions or equations for thermal stress are scarce (Johannessen et al., 1982). A very recent literature review showed that most considerations on thermal expansion were not beyond the conceptual level, and that the opinions were often contradictory (Gonçalves and Brito, 2016). It is necessary to accurately understand the role of thermal expansion in salt weathering process, although this mechanism was previously thought to be less effective than the other two (Laity, 2008).

The methods of weathering research include field monitoring, laboratory testing, dating, and modeling. As pointed out by Viles (2011), an advantage of modeling is that it can address questions at any temporal and spatial scale. For instance, the growth of tafoni due to crystallization has been simulated under the condition of wetting/drying cycles (Huink et al., 2004). In the current study, a simple model was established by using the traditional plate theory in solid mechanics to estimate the thermal stress caused by a superficial salt layer on the rock substrate.

Salt weathering is common in the arid region of northwestern China. Fig. 1 shows the tafoni at (40°3′12″N, 100°8′20″E) in the southwestern margin of the Badain Jaran Desert. These typical cavernous weathering features, which form on sandstones, cover an area of 1200 km² approximately. The diameters and depths of tafoni can change from a few centimeters to several meters, see Fig. 1(a). Similar to those found in the Atacama Desert of Chile (Viles, 2011), salt deposits also occur within most tafoni in the Badain Jaran Desert, see Fig. 1(b). The widely distributed saline playas in this region are being subjected to active aeolian processes (Wang et al., 2013). Some previous studies discovered that aeolian sediments on the ground or in the air could contain remarkable salts (Abduwaili et al., 2008; Wang et al., 2008; Zhu et al., 2012). Therefore, aeolian deposition of saline dust is an evident source of the superficial salt layers in the study area.

Phenomenological models describing the processes of salt weathering and tafoni evolution can be established, according to the geometrical, thermal and mechanical properties of materials and the...
principles of solid mechanics (Hetnarski and Eslami, 2009; Eslami et al., 2013). Most substances, including rocks and salt layers in this study, deform when their temperature changes. For a wide range of temperatures, this deformation is proportional to temperature change. The coefficient of linear thermal expansion $\alpha$ is thus defined as the length change of a bar of unit length per unit temperature change. A simplified model for the thermal deformation of a superficial salt layer within a tafone is illustrated in Fig. 2. To estimate the thermal stress acting on the rock substrate, we made two assumptions as follows: (1) The salt layer and rock are completely composed of homogeneous elastic and rigid materials, respectively. This assumption is based on the fact that many common desert salts deform to a much greater degree than those of rocks which are subjected to the same temperature change (Cooke and Smalley, 1968; Goudie, 2013). Consequently, salt deposits within a tafone can be modeled by an elastic material restricted by a rigid body, as shown in Fig. 2(a). (2) The thickness $h$ of the salt layer is small compared with its diameter $2a$. Field measurements suggest that $h/a \approx 10$. This geometrical characteristic suggests that the mechanical behavior of salt layers can be well described by the plate theory in solid mechanics.
Our objective is to obtain the lateral distributed load \( p \) exerted on the lower surface of a salt layer by a rock substrate. From the viewpoint of mathematics, it is convenient to analytically solve this problem in terms of displacements rather than internal forces, because the number of governing equations is minimal. For two special bending cases of an identical circular plate solely subjected to thermal and mechanical loads in cylindrical coordinate systems, as shown in Figs. 2(b) and (c) respectively, both deflections are governed by the standard two-dimensional biharmonic equation (Ventsel and Krauthammer, 2001; Eslami et al., 2013). The boundary condition must be given in order to derive two deflection expressions: (1) the edge deformation of the salt layer is restricted by the sidewall, (2) the assembled salts at \( r = a \) can locally solidify and strengthen the salt layer, when water evaporates from the sidewall into the atmosphere. Hence an approximation allows the boundary condition at \( r = a \) to be zero displacement.

For a circular plate with simply supported edge under a uniform thermal load shown in Fig. 2(b), the deflection \( w_1 \) defined as the displacement component of points in the middle surface of the plate occurring in \( z \) direction, can be expressed by (Eslami et al., 2013),

\[
w_1 = \frac{M_T}{2(1-\nu^2)D} \left( a^2 - r^2 \right)
\]

where \( v \) and \( D \) are Poisson’s ratio and the bending rigidity of the plate, respectively. \( M_T \) is the thermally induced resultant moment. Strictly speaking, the temperature change within the salt layer should be determined by the laws of insolation and heat conduction. In this estimation, we assume that the initial temperature is a constant and that the temperature profile in \( z \) direction is linear. \( T_0 \) and \( T_a \) are the temperature terms at two faces of \( z = h/2 \) and \( z = -h/2 \). The expressions of \( D \) and \( M_T \) are,

\[
D = \frac{Eh^3}{12(1-\nu^2)}
\]

and

\[
M_T = \frac{\alpha Eh^2}{12} (T_b - T_a)
\]

where \( E \) is the elastic modulus.

For a circular plate with simply supported edge under a uniform mechanical load \( p \) shown in Fig. 2(c), the deflection \( w_2 \) can be written as (Ventsel and Krauthammer, 2001),

\[
w_2 = \frac{p}{64D} \left( a^2 - r^2 \right) \left( \frac{5 + \nu}{1 + \nu} \right) \left( a^2 - r^2 \right)
\]

The influences of thermal and mechanical loads on deflections are opposite. Let the maximum deflections be equivalent under two conditions, i.e. \( w_1 |_{r=a} = w_2 |_{r=a} \). We have,

\[
p = \frac{8\alpha E(T_b - T_a)}{3(5 + \nu)(1 - \nu)} \frac{h^2}{a^2}
\]

in which the expressions (2) and (3) have been taken into account.

Eq. (5) can be used to estimate the thermal stress generated by the salt layer. Given radius-thickness ratio as small as possible and extreme temperature difference, e.g. \( a/h = 10 \) and \( T_b - T_a = 50 \) K, the utmost thermal stress will be obtained. Three material parameters can be conveniently found in the literature (Tesárek et al., 2003; Gercek, 2007; Liang et al., 2012) or on the internet (The Engineering Toolbox, 2016). Here the appropriate values are chosen to be \( \nu = 0.25 \), \( E = 2.27 \) GPa, \( \alpha = 40.4 \times 10^{-6} \) K\(^{-1}\) for halite and \( \nu = 0.34 \), \( E = 4.05 \) GPa, \( \alpha = 7.22 \times 10^{-4} \) K\(^{-1}\) for gypsum. Thus the utmost thermal stresses induced by halite and gypsum are calculated to be 31.1 kPa and 11.1 kPa, respectively. However, the yield stress of common rocks is generally larger than 10 MPa (Jeng et al., 2002; Liang et al., 2012; The Engineering Toolbox, 2016). It can be seen that the obtained thermal stress and the known yield stress of rocks differ by three orders of magnitude at least. As a general conclusion, the thermal expansion of superficial salt layers is difficult to cause rock breakdown.

Recently, (Gonçalves and Brito, 2016) distinguished thermal expansion damage models at the micro and macro scales. A rough estimation of the shear stress at the interface of superficial salt layer and limestone in their macroscopic-level model, probably similar to Fig. 2(a), also revealed that thermal expansion could not cause detachment of salt-loaded layers. For the “microscopic” case of individual salt crystals in the crevices and pores of rocks, as proposed by (Cooke and Smalley, 1968), thermal expansion was concluded to be an effective mechanism based on the thermal stress they estimated (Gonçalves and Brito, 2016). An interesting problem will arise if their assumptions and derivations are perfectly acceptable. There should have a spatial scale range within which thermal expansion mechanism works well. More accurate mechanical models, for which detailed information on the distribution and restriction of salts is likely crucial, are needed to approach this subject. Homogeneous materials were assumed both in our and Gonçalves-Brito’s macroscopic-level models. In fact, local stress concentration could be caused by the nonhomogeneity of material and mechanical properties. Fatigue rupture due to repeating temperature change could also occur, although the thermal stress of salt expansion is always smaller than the yield stress of rocks. These two effects should be further investigated by modeling thermal expansion mechanisms.

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