Comment on ``Cavitation during desaturation of porous media under tension'' by Dani Or and Markus Tuller

Article *in* Water Resources Research · November 2003

DOI: 10.1029/2002WR001834

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Comment on "Cavitation during desaturation of porous media under tension" by Dani Or and Markus Tuller

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Received 8 November 2002; revised 15 July 2003; accepted 14 August 2003; published 1 November 2003.

INDEX TERMS: 1878 Hydrology: Water/energy interactions; 1866 Hydrology: Soil moisture; 1875 Hydrology: Unsaturated zone; *KEYWORDS:* soil moisture, unsaturated zone, water/energy interactions, drainage (of porous media), cavitation, capillary pressure

Citation: Toker, N. K., J. T. Germaine, and P. J. Culligan, Comment on ''Cavitation during desaturation of porous media under tension'' by Dani Or and Markus Tuller, *Water Resour. Res.*, *39*(11), 1305, doi:10.1029/2002WR001834, 2003.

1. Introduction

[1] A potential mechanism for liquid drainage of porous media based on cavitation of water under tension was proposed by *Or and Tuller* [2002]. In their technical note, Or and Tuller correctly recognize that there are two mechanisms of drainage in porous media, namely, air entry into a soil surface and cavitation in the soil pore space. They also correctly note that techniques for determining a soil moisture characteristic (SMC) that apply positive pressure on the soil pore water do not simulate cavitation. However, the basis for the formulation that Or and Tuller use in their technical note does not correspond to the mechanisms of cavitation and drainage that they describe (addressed here in section 3). Of less practical importance is the fact that the authors miss a vital detail in the formulation of energy of formation of a bubble in water (addressed here in section 2).

2. Vapor Pressure Term in Energy Equation

[2] The energy required to form a vapor bubble is given by *Or and Tuller* [2002] as equation (1), which is a simplified form of the equation [*Fisher*, 1948]

$$\Delta E = 4\pi r^2 \sigma + \frac{4\pi}{3} r^3 \left(P_w - P_{\mathrm{vapor}}\right). \tag{1}$$

Or and Tuller's equation (1) is conventionally used for water tensions in the MPa range because in this range, P_w is much larger than the vapor pressure (P_{vapor} = 2645 Pa at 22°C). However, Or and Tuller use their equation (1) to obtain formation energy ΔE versus bubble radius curves for water tensions as low as 10 kPa, 1 kPa, and 100 Pa. In these cases, the water tension is of the same order of magnitude as the vapor pressure, and hence omitting the vapor pressure term leads to a large error in calculation. Accounting properly for P_{vapor} changes the ΔE versus r curves radically, especially for small water tension values. Fortunately, making this correction does not change the general shapes or trends of the curves given by Or and Tuller's Figure 1. It also does not conflict with the main ideas presented in the technical note.

[3] Our Figure 1 illustrates this point by plotting curves using both *Or and Tuller*'s [2002] equation (1) and our equation (1). Or and Tuller's energy barriers for water tensions of 100 and 1000 Pa are in error by order(s) of magnitude. However, as the P_w term becomes dominant (as it does at 10,000 Pa), the error is reduced. Figure 1 also illustrates the critical radii for each water pressure and corresponding formation energies. These are the loci of points at limit force equilibrium. It should be noted that plotting $\Delta E/kT$ as the ordinate could be more informative, but this has already been done in many other sources [e.g., *Fisher*, 1948; *Maris and Balibar*, 2000].

3. Initiation of Desaturation of Porous Media

[4] In section 2 we point out a technical error that *Or and Tuller* [2002] make in calculating the formation energy of vapor bubbles in a pure liquid under tension. In this section we argue against the hypothesis put forward by Or and Tuller to explain the drainage of a porous medium by cavitation.

3.1. Cavitation Mechanism

[5] We agree with *Or and Tuller* [2002] that at a certain value of water tension, if a bubble exists at a size larger than the critical radius corresponding to the maximum energy of formation at that particular magnitude of water tension, it undergoes spontaneous unlimited expansion. However, in their note, Or and Tuller define no mechanism for the formation of bubbles in the first place. In other words, bubbles just ''appear'' in Or and Tuller's model. The technical note assumes a final condition with a bubble of water vapor that is the same size as a soil pore. This size also corresponds to the critical radius, i.e., the bubble that requires the highest energy to form. Information on how this bubble might have formed, climbing up the energy barrier as it expanded from zero radius to the critical radius, is lacking.

[6] Papers referenced by *Or and Tuller* [2002], such as *Zheng et al.* [1991] and *Speedy* [1982], use the same bubble

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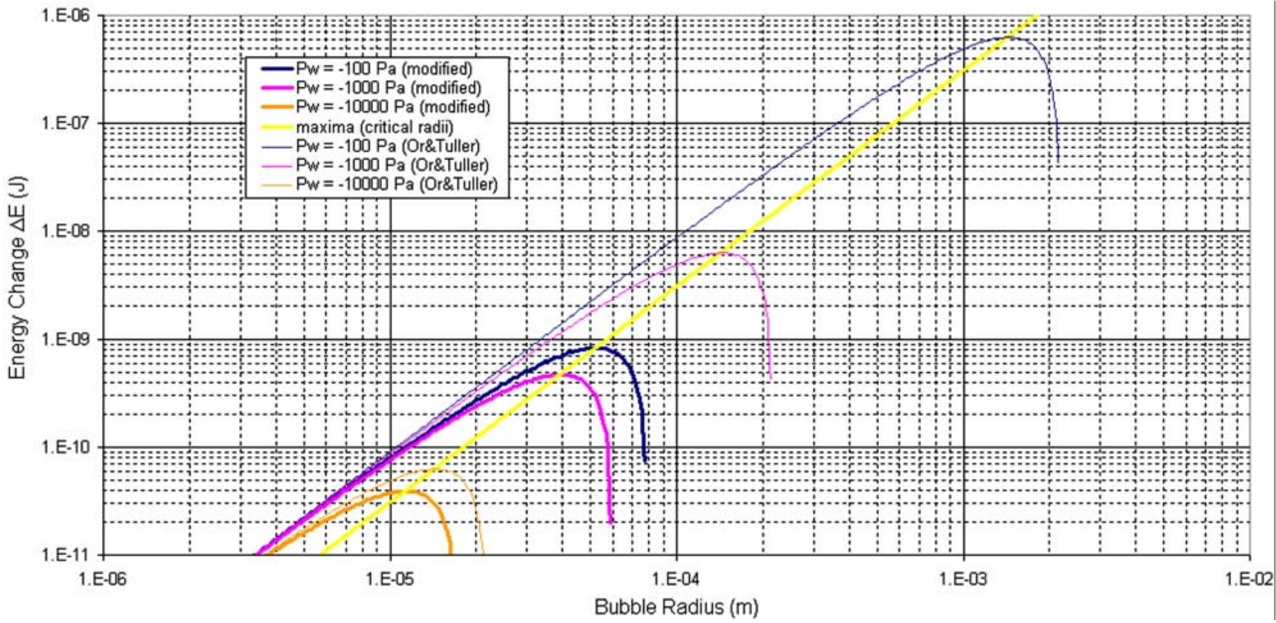

Figure 1. Figure 1 of *Or and Tuller* [2002], replotted with both old and corrected energy barriers. Corrected energy barriers are modified from the old plots by including vapor pressure in the calculations as in our equation (1).

formation energy formulation for cavitation in a pure water phase and calculate the tensile strength of water as 140 MPa. *Fisher* [1948], whose study inspired Zheng et al. and Speedy, reports a similar tensile strength for a pure water phase. According to these references, no bubble can form in pure water under tension magnitudes <140 MPa. As noted by Or and Tuller, according to *Maris and Balibar* [2000], there is a probability of water cavitation at lower pressures in response to a thermal fluctuation. Nonetheless, even at the highest water tension level discussed by Or and Tuller (10 kPa), this probability is of the order of $10^{-4.5\times10^9}$, in other words, effectively zero.

[7] In practice, cavitation occurs at a lot less than 140 MPa in natural porous media (soils), confirming that cavitation of water in soil pores is not controlled by the mechanism formulated by *Fisher* [1948], *Zheng et al.* [1991], and *Speedy* [1982]. In the pore space of the soil, instead of forming in pure water the cavitation initiates from a weak point, such as existing microbubbles (nuclei) of air in the pores. This necessity of heterogeneous nucleation for cavitation is also quoted by *Or and Tuller* [2002] in section 4 of their technical note with references to *Miller* [1973, 1994] and *Atchley and Prosperetti* [1989].

3.2. Effects on Drainage and SMC Curves

[8] As *Or and Tuller* [2002] emphasize, there are two completely different mechanisms for water drainage of a porous matrix. Capillary drainage is the air entry mechanism, which is the only mechanism that positive pressure techniques (porous plate, pressure membrane, etc.) for SMC determination are able to simulate.

[9] The second mechanism is cavitation; however, its influence on the SMC curve is difficult to analyze and impossible to simulate under positive pressure. The existence of bubbles in a soil specimen and cavitation initiating from them will affect the SMC curve. The size of an initial air bubble determines not only the magnitude of tension the pore water can withstand but also, at a smaller scale, the amount of water in the pore. This means that the initial state of a soil specimen containing air bubbles cannot be placed correctly on the drainage curve (matric suction-water content) coordinate system because the amount of entrapped air prior to drainage is indeterminate [*Chahal and Yong*, 1965]. The inability of the positive pressure techniques to simulate cavitation was first noted and was extensively demonstrated experimentally by *Chalal and Yong* [1965].

[10] As mentioned by *Or and Tuller* [2002, section 4] a secondary effect could result from the variation of solubility of air in water with pressure and tension. When time effects are considered, this further increases the difference between an SMC curve obtained under pressure and the actual SMC curve. Pressurizing an existing bubble causes the air to dissolve, further diminishing the bubble, whereas a bubble under tension will receive additional air coming out of solution because of reduced solubility, expanding the bubble further.

[11] Even if the cavitation is assumed to nucleate in the middle of pure bulk water, the mechanism proposed by *Or and Tuller* [2002] does not explain the drainage of porous media. Given that the probability of homogeneous nucleation is $10^{-4.5\times10^9}$, if it does occur, it will not happen simultaneously in all of the thousands of pores of the medium; it will happen in only one (or two). The resultant expansion of vapor bubbles at a few locations will not go beyond the nearby pore necks, effectively preventing further drainage at that level of suction. Drainage of a couple of pores will not make a measurable difference in the water content of the system; therefore it will not cause the drainage at constant suction presented in Or and Tuller's Figure 3. A more realistic scenario would be a "bubble trapped in crevice" model [e.g., *Atchley and Prosperetti*, 1989], which assumes the existence of air-filled micro-

crevices in all of the soil pores initially. Energy barrier calculations from this initial point, parallel to those presented in the technical note for homogenous nucleation, might lead better to the desired analytical simulation of drainage.

4. Summary and Conclusions

[12] The contribution of *Or and Tuller* [2002] in emphasizing the insufficiency of SMC determination techniques that rely on pressure systems to simulate the actual drainage mechanism of porous media is acknowledged and supported. We agree with the main ideas and conclusions of the technical note, although the proposed mechanisms for cavitation and drainage of a porous medium deserve more thought.

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