Response to “Discussion on “Evaluation of the swelling characteristics of bentonite-sand mixtures””¹

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The swelling of bentonite-sand mixtures is mainly induced by the montmorillonite absorbing water. We assumed in the original paper ([Sun et al., 2015](#)) that non-montmorillonite clay in the bentonite did not absorb any water. The important base of evaluating the swelling characteristics of bentonite-sand mixtures was that the maximum amount of water absorbed by montmorillonite per unit volume was constant under a certain stress after swelling reached a stable state, and it was independent of the initial dry density and initial content of water or sand ([Sun et al., 2009](#)).

In the original paper ([Sun et al., 2015](#)), the authors actually assumed that all the pores and available water were associated with the montmorillonite fraction and used a state parameter “montmorillonite void ratio e_m ” proposed by [Sun et al. \(2009\)](#). However, it was not the only premise or state parameter. The critical sand content α_s was also introduced as a limit. For bentonite-sand mixtures with less sand than the critical sand content, the sand skeleton will not form and the unique linear $\log e_m - \log \sigma_v$ relationship is valid under any vertical stress, but when the sand content is more than the critical sand content, a sand skeleton will form at a certain vertical stress.

As mentioned in [Sun et al., 2015](#) and the Discussion ([Schanz et al., 2016](#)), some swelling results from different types of bentonite-sand mixtures with less sand than the critical sand content satisfy the unique linear $\log e_m - \log \sigma_v$ relationship. However, when the sand content exceeds the critical sand content, very low bentonite contents can lead to mixture inhomogeneity, or an uneven bentonite distribution within the mixture, and the swelling of mixtures expressed in terms of the montmorillonite void ratio deviates from the unique linear $\log e_m - \log \sigma_v$ relationship above a ‘starting deviation stress’ σ_s which depends on the sand content. According to a predictive method suggested and verified in [Sun et al., 2015](#), the swelling due to saturation of bentonite-sand mixtures where the sand content is down to 10% can be predicted. [Mollins et al. \(1996\)](#) conducted one-dimensional swelling tests on pure bentonite and mixtures with 80, 90 and 95% sand contents

by weight. Here the authors supplement the prediction of experimental data by Mollins et al. (1996). Fig.1(a) normalizes the swelling test data with montmorillonite void ratio, Fig.1(b) shows the prediction of ‘starting deviation stress’ for Wyoming bentonite-sand mixtures with different sand contents, and Fig. 1(c) is the prediction of $e_m - \sigma_v$ relationship for mixtures with more sand than the critical sand content. The relevant parameters used for the swelling prediction are listed in Table 1.

Fig. 1 Swelling prediction for Wyoming bentonite-sand mixtures

Table 1 Relevant parameters for swelling prediction of Wyoming bentonite-sand mixtures

Type of Mixture	ρ_m	ρ_{nm}	ρ_{sand}	β	e_{smax}	a	b	α_s	φ
	(g/cm ³)			(%)				(%)	
Wyoming bentonite-sand mixtures	2.76*	2.67*	2.67*	85**	0.978**	0.473	0.389	49.3	-13.11

* Mollins et al. (1996); ** Mollins (1996).

Note: ρ_m , ρ_{nm} and ρ_{sand} : the density of montmorillonite, non-montmorillonite clay minerals and sand respectively; β : the content of montmorillonite in bentonite; e_{smax} : the maximum void ratio of sand; a , b : the material parameters in the linear relationship $\log e_m = a - b \log(\sigma_v / p_a)$, where p_a is atmospheric pressure in kPa; α_s : the critical sand content; φ : the parameter linked to stress distribution coefficient, as shown in Eq. (13) in Sun et al., 2015.

Schanz et al. (2005) proposed the plausible mechanism for pore water redistribution where most of the water located in the macro-pores initially would be redistributed to the micro-pores

gradually due to the suction gradient with elapse time, while the suction would increase from an initially quasi-equilibrium state to a higher total suction. This condition occurs when water inflow into soils is relatively fast. In [Schanz et al. \(2005\)](#), the swelling development process is concerned. Moreover, the discussers suggested that the swelling characteristics of bentonite-sand mixtures depend upon the applied compaction energy, the induced swelling pressure (bentonite content) and applied stress in the Discussion ([Schanz et al., 2016](#)).

It is true that many factors can influence the swelling of mixtures simultaneously, apart from several factors mentioned above, as well the type of bentonite, the bentonite content in the mixture, the deformation of voids among sand particles due to stress, and whether the macro-pores are invaded completely or partly by swollen bentonite, and so on. However, in the predictive method ([Sun et al., 2015](#)), the authors avoid considering the apparently complicated swelling processes during water uptake, but just consider the changes between two states, one is the initial unsaturated state, and another is the final saturated state.

To better understand, the authors manage to describe the predictive method briefly. When the sand content is less than the critical sand content, sand particles are dispersed within the bentonite. The linear $\log e_m - \log \sigma_v$ relationship, which represents the final saturated state line, is valid under any vertical stress. Once this unique line is determined, the relationship between the final void ratio and the vertical stress ($e_f - \sigma_v$) after full wetting for mixtures with a specified sand content can be obtained. According to the $e_f - \sigma_v$ relationship, the deformation after full wetting (swelling or collapse) under any vertical stress can be judged for mixtures at any initial state, whether highly compacted or lowly compacted.

When the sand content is higher than the critical sand content, the swelling of mixtures expressed in terms of clay/montmorillonite void ratio deviates from the bentonite behaviour above a stress, which has been observed and identified by many researchers ([Mollins et al., 1996](#); [Sun et al., 2009](#); [Sun et al., 2013](#)). In [Sun et al., 2015](#), the authors normalized the swelling with the montmorillonite void ratio and proposed a predictive method to determine the $e_m - \sigma_v$ relationship for mixtures with more sand than critical sand content $\alpha > \alpha_s$. Based on the $e_m - \sigma_v$ relationship shown in Fig. 2(a), the relationship between the final void ratio and the vertical stress ($e_f - \sigma_v$) after full wetting, for mixtures with a specified sand content, can also be obtained as shown in Fig. 2(b). Fig. 3 shows the swelling results in $\log e - \log \sigma_v$ coordinate for Kunigel V₁ Na bentonite-sand mixtures with the high sand contents obtained by [Sun et al. \(2009\)](#). Comparing the initial state to the final saturated state, the deformation due to wetting, swelling or collapse, of mixtures with more sand than the critical sand content can be finally judged.

Fig. 2 Swelling prediction for bentonite mixed with more sand than critical sand content

Fig. 3 $e_f - \sigma_v$ relationship of bentonite mixed with more sand than critical sand content

Fig. 4 shows the $e_f - \sigma_v$ relationship of the mixture with α sand content ($\alpha > \alpha_s$) with the initial higher dry density (Fig. 4a) or lower dry density (Fig. 4b), and the initial void ratio of mixtures equals e_0 . The solid line represents the $e_f - \sigma_v$ relationship transferred from the predicted $e_m - \sigma_v$ relationship, as shown in Fig. 2(a). The corresponding swelling pressure equals p_s and the starting deviation stress equals σ_s . The following analysis is based on the premise that the montmorillonite fills the sand skeleton voids completely.

Fig.4 Sketch of $e_f - \sigma_v$ relationship of bentonite-sand mixtures with α sand content ($\alpha > \alpha_s$)

For highly compacted mixtures (Fig. 4a), the sand skeleton may have existed already. When a specimen is wetted under a vertical stress σ_{v1} that was less than σ_s , i.e., $\sigma_{v1} < \sigma_s$, montmorillonite exists in the voids of sand skeleton and swells, the specimen will not swell until e_f reaches the e_f - σ_v relationship. At this condition, the vertical stress is borne by the montmorillonite.

When a specimen undergoes a vertical stress σ_{v2} that is greater than σ_s , i.e., $\sigma_{v2} > \sigma_s$, however, σ_{v2} is less than the swelling pressure p_s , i.e., $\sigma_{v2} < p_s$, montmorillonite in the voids of sand skeleton swells, and the tightened contact among sand particles is released by the swelling of montmorillonite, however, the sand skeleton still exists. At this condition, the total deformation of specimen is swelling, and the stress applied is borne by both the montmorillonite and the sand skeleton.

When a specimen undergoes a vertical stress σ_{v3} greater than p_s , i.e., $\sigma_{v3} > p_s$, the sand skeleton is compressed, and the montmorillonite and the sand skeleton support the vertical stress.

For lowly compacted mixtures (Fig. 4b), when a specimen is wetted under a vertical stress σ_{v1} , a sand skeleton will not form, and the specimen will swell until e_f reaches the e_f - σ_v relationship. At this condition, the vertical stress is borne by the montmorillonite.

When a specimen undergoes a vertical stress σ_{v2} greater than the swelling pressure p_s , i.e., $\sigma_{v2} > p_s$, however, σ_{v2} is less than σ_s , a sand skeleton will not form, and the montmorillonite bears all the vertical stress and is compressed. Hence, the collapse will occur after swelling under applied stress and sand particles remain dispersed among the montmorillonite.

When a specimen is wetted under σ_{v3} higher than σ_s , a sand skeleton will form, montmorillonite existing in the sand skeleton swells to invade the voids either completely or partly. At this condition, collapse will occur after swelling and sand particles remain fully in contact.

So far, we discuss further the swelling analyzing method proposed in [Sun et al., 2015](#) concerning the factors such as the initial compaction energy, the vertical stress and the swelling pressure. The predictive method is valid when saturated bentonite completely fills the sand skeleton voids, as has already been verified ([Sun et al., 2015](#)). In case of sand-bentonite mixtures with a very low bentonite fraction, bentonite may not be sufficient enough to fill all the voids of sand skeleton, and some free water may exist in the remaining voids. In this situation, the predicted results will be higher than the actual swelling, just as the results for Wyoming bentonite-sand mixtures with 95% sand shown in Fig.1(c). With the increase of the vertical stress, the void ratio of sand skeleton decreases, and the free water existing in the voids is squeezed out, and the deformation is totally caused by the compression of sand skeleton. Once the saturated bentonite completely fills the sand skeleton void ratio, the predictive method will be applicable.

In conclusion, the predictive method proposed in [Sun et al., 2015](#) is based on the assumption that

all the pores and available water are associated with bentonite fraction, and it has been verified to predict the swelling of bentonite-sand mixtures with higher bentonite fraction than the “limiting clay content” as mentioned in the Discussion (Schanz et al., 2016). However, when the bentonite fraction is less than the limiting clay content, saturated montmorillonite cannot fill in voids of the sand skeleton, and the assumption will not be valid until the saturated montmorillonite fills the sand skeleton voids again at a higher vertical stress. In order to predict the swelling of mixtures with an extremely small amount of bentonite, we are managing to build a modified predictive method based on Sun et al, 2015.

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