Effects of coupled hydro-mechanical model considering two-phase fluid flow on potential for shallow landslides: a case study in Halmidang Mountain, Yongin, South Korea

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We thank the referee for their insightful comments which truly helped enrich the manuscript. In the revised manuscript, we have clarified contributions of the manuscript. We have also added detailed descriptions of the methodology. For the comments raised by the reviewer, we have provided the point by point responses.

Referee #2's Comments	Responses
The research lacks the detailed information and the full evidences explaining the reason why the coupled hydro-mechanical model is better the single-phase flow model.	Numerous previous studies have proved that the coupled hydro-mechanical model could simulate infiltration behavior more appropriately than the single-phase flow model (e.g., Hu et al., 2011, 2016, 2018; Wu and Selvadurai, 2016). We added the following sentences explaining usefulness of the coupled model compared to the single-phase model in Line 49–55. *"Because air flow delays wetting process on soil slope associated with rainfall infiltration (Hu et al., 2011), a neglect of air flow would result in an imprecise simulation (Laloui et al., 2003), such as an overestimation of deformation induced by rainfall infiltration (Hu et al., 2016). Effects of deformation on water retention behavior should be considered in the collapse during wetting process (Hu et al., 2016). Water retention curve hysteresis is fundamental for the soil–water–air coupling (Ebel et al., 2010; Tsai, 2011; Borja et al., 2012; Yang et al., 2017), and it has significant effects on distribution of water content and slope stability (Ma et al., 2011)."*

	We also demonstrated that the coupled hydro-mechanical model simulated the experimental results obtained from Liakopoulos (1964) quite accurately in the section 5.1. Our purpose is to propose a simplified method applicable to the shallow landslide assessment at a regional scale utilizing the fully coupled hydro-mechanical model and to check the applicability of the method in forecasting shallow landslides at a regional scale. We added detailed descriptions of the coupled hydro-mechanical model composed of three loops (i.e., fluid flow, mechanical, and water retention model loops are sequentially applied to each time step) in the section 4.1. Descriptions of all the equations used in the coupled model and how to apply the model to 2-D infinite slopes are also given in the same section. We also added descriptions of how to conduct the slope stability analysis using results from the coupled model in the section 4.2.
In line 7, compared to the detailed information in section of study area, "More than 30 shallow landslides" is not clear. Please revise it.	We changed "More than 30 shallow landslides" to "36 shallow landslides" in Line 7.
The accuracy comparison. In line 17, your result with coupled hydro-mechanical model is "slightly" more consistent with the single-phase flow model. Although your presentation in the whole paper is good, the result is just slightly better. Also in Line 314 and line 317, the accuracy comparison of 0.89 vs 0.86 and 90.7% vs 91%. What is the meaning of your research?	Even though results from the coupled hydro-mechanical model is just slightly better than those from the single-phase flow model, it is necessary to apply improved methodology to simulate the actual phenomenon more accurately. While rainfall infiltrates into soils, both air existing in void spaces and changes in area of void spaces caused by soil deformation affect rainfall infiltration rates. We tried to propose a simplified method applicable to the shallow landslide assessment at a regional scale utilizing the fully coupled hydro-mechanical model and checked its usefulness in a forecast of slope failure applying it to actual landslide events in

Korea. We revised the following sentences in Lines 49–66 to clearly describe the reason why we applied the coupled model and the contributions of this work.

"Because air flow delays wetting process on soil slope associated with rainfall infiltration (Hu et al., 2011), a neglect of air flow would result in an imprecise simulation (Laloui et al., 2003), such as an overestimation of deformation induced by rainfall infiltration (Hu et al., 2016). Effects of deformation on water retention behavior should be considered in the collapse during wetting process (Hu et al., 2016). Water retention curve hysteresis is fundamental for the soil–water–air coupling (Ebel et al., 2010; Tsai, 2011; Borja et al., 2012; Yang et al., 2017), and it has significant effects on distribution of water content and slope stability (Ma et al., 2011). Whereas it has been demonstrated that the coupled hydro-mechanical model considering two-phase fluid flow and deformation-dependence of water retention behavior with hydraulic hysteresis accurately simulates the behavior of unsaturated deformable soils at a slope scale (e.g., Hu et al., 2016; Hu et al., 2018), such models have rarely been applied to evaluate slope stability on a regional scale.

We proposed a simplified method applicable to the shallow landslide assessment at a regional scale utilizing the fully coupled hydro-mechanical model and checked its usefulness in a forecast of slope failure applying it to actual landslide events in Korea. Considering efficient uses of computing resources, we simplified slopes at cells of the GIS-based topography of Halmidang Mountain located in Yongin-si, South Korea to be infinite slopes in a two-dimensional domain. We applied the coupled hydro-mechanical model based on numerical

	methods to those infinite slopes for suitable simulations of slope failure induced by rainfall infiltration. The changes in pore air/water pressures and void ratios obtained from the simulation of rainfall-infiltration were used as input data for slope failure analyses at each infinite slope model, and the minimum safety factor on the infinite slope was determined to be a safety factor of the corresponding cell of the GIS-based topography."
In line 65, the paper mentioned the outcropping lithology. This area only includes two kinds of lithology, or this two lithology are the main types? Detailed lithology information should be described, better with a map, if necessary.	The mountainous area in the study area only includes two kinds of lithology (biotite gneiss and Pre-Cambrian Era banded biotite gneiss). We added Figure 2(a) that shows geological map of the study area and revised the following sentence in Lines 78–81 to complement the lithology information. *"The outcropping lithology of Halmidang Mountain consists of biotite gneiss (Bgn) and Pre-Cambrian Era banded biotite gneiss (PCEbngn), and that of the area surrounding the mountain consists of quaternary alluvium (Qa) and Quartzofeldspathic gneiss (Qgn), as shown in Figure 2(a) (Geological Survey of Korea, 1972; Korea Institute of Energy and Resources, 1982)."*
In line 71, 36 shallow landslide occurred at Halmidang Mountain. In line 73, debris flow occurred along 21 watersheds. In line 89 landslide inventories comprise information. In line 90, you applied performance evaluation. In line 93, you checked the accuracy of the landslide inventories. Please add the landslide inventory in this manuscript. What are types of these 36 natural hazard? As I cannot understand the meaning of landslide in your manuscript. The landslide means the natural hazards in the broad concept, or specific debris	In this study, the inventory means the locations where shallow slope failures initiated. The inventory map composed of slope failure occurrence points is shown in Figure 2(b). We will provide it as an electronic supplement which can usefully be utilized in other studies. We stated debris flows, which were initiated from 29 out of 36 slope failure occurrence areas and spread along 21 watersheds, to describe overall landslide damage in the study area. For clarity, we revised the following sentences in Lines 108–110. *"From 29 out of 36 slope failure occurrence areas, debris flows were transformed and spread along 21 watersheds with a total debris flow spreading area*

flow. Also please simply describe the work of performance evaluation. Please describe the accuracy of the landslide inventories.	*of approximately 94,000 m². Spreading area and distance of each debris flow ranged from 1,100 to 19,600 m² and from 90 to 580 m, respectively."*
	As we described in the following sentence in Lines 106–108, 36 natural hazards were used as slope failures in this study.
	"We built a total of 36 slope failure initiation sites in the GIS format (as shown in Figure 2(b)) by comparing satellite images with a 5-m resolution of the area of Halmidang Mountain which were taken before and after the landslide events in 2011."
	The performance evaluation of models for a shallow slope failure prediction is conducted by comparing the inventory map with the locations of slope failure prediction areas. We already described it in the following sentence in Lines 104–106.
	"Landslide inventories comprise information in terms of slope failures and are also important sources of data used to compare the information with the locations of potential slope failure areas predicted by slope stability assessments for performance evaluation."
	We checked the accuracy of the landslide inventories by visiting actual slope failure occurrence sites and comparing coordinates of the inventories with those measured at the site during our field investigations. We added Figure 2(c) showing two actual slope failure sites we observed. We revised the following sentence in Lines 109–110 to clearly describe how to check the accuracy.
	"We checked the accuracy of the landslide inventories by comparing coordinated of some of them with actual coordinates of slope failure sites that we measured during our field investigations."

In line 200-206, I cannot understand how to make the figure6 and figure7? To be specific, in the zone 1 of figure 6, there are eleven points in the time line of 0h. Could you please describe it?	In Figure 8 and Figure 9, eleven points you mentioned display profiles of pore water/air pressure or matric suction at 0, 4, 8, 12, 16, 20, and 22 hours from starting rainfall at depths from ground surface (0 m) to 2 m with 0.2-m intervals at the middle of infinite slope. From results of infiltration analysis on the infinite slope, the profiles of pore water/air pressure or matric suction could be obtained. *Figure 6 and Figure 7 were changed to Figure 8 and Figure 9, respectively, in a revised manuscript.
In the line 204, why you set the infinite slope 30°? The case study is a regional area. Are the conditions in the 12 zones the same?	Figure 8 and Figure 9 show just examples of infiltration behaviors at the infinite slope with an angle of 30°. As we stated in Lines 300–301, the angle of 30° was just considered because it is similar to the average slope angle at actual slope failure sites in the study area with a value of 27°. Actually, however, numerous infinite slopes were modeled depending on slope angles of different cells of the slope raster computed from the DEM in the study area, as described in sentences in Lines 214–216.
In section 5.3.1, you aim to compare the coupled hydro-mechanical and single phase flow model. Please do not neglect the parameter sensitivity. For example, in figure 6, the plot of line and point are very similar in zone 1, zone 3 and zone 8. I see the parameters in Table 2, the parameters are not similar. Please explain.	Geotechnical parameters of zone 1, zone 3, and zone 8 are not similar in Table 2, but an infiltration behavior is almost dependent on hydraulic properties, such as saturated hydraulic conductivity and relative permeability. Values of saturated hydraulic conductivity of zone 1, zone 3, and zone 8 are almost the same (i.e., 4.74×10^{-5}, 4.9×10^{-5}, and 4.89×10^{-5} m/s). Relative permeability curves of zone 1, zone 3, and zone 8 are also similar, as shown in Figure 7. We also added Figure 13 and the following sentences in Lines 422–436 to describe results of the sensitivity analysis. "*Limited number of samples were used to determine representative material properties of the study area in spite of complex geological features and variability in material properties. We investigated effects of cohesion (c), saturated hydraulic*

	conductivity (k_s), water retention model parameter (k_p), and van Genuchten SWRC coefficient (a) on characteristics of change in safety factor. Figure 13 shows variations in safety factor with time at an infinite slope model with an angle of 30° when material properties of Zone 10 were consistently applied with the exception of changing only c or k_s or k_p or a. As a value of cohesion became large from 0 to 9 kPa, an initial safety factor increased from 1.4 to 1.95 (Figure 13(a)). The rates of decrease in safety factor were not affected by cohesion. It is observed in Figure 13(b) that safety factors slowly and continuously decreased when saturated hydraulic conductivity was small ($k_s = 3 \times 10^{-5}$ m/s). However, the greater the saturated hydraulic conductivity, the larger the reduction in safety factor when rainfall occurred (from 0 to 5 h and from 12 to 22 h), and the smaller the reduction in safety factor when rainfall did not occur (from 6 to 11 h). When the water retention model parameter decreases, an air entry pressure (P_0) becomes large, and a rate of increase in degree of saturation with a decrease in matric suction becomes fast. Therefore, the smaller the water retention model parameter, the faster the reduction in safety factor (Figure 13(c)). As a van Genuchten SWRC coefficient increases, the slope gradient of water retention curve becomes steep, and a degree of saturation at the same matric suction becomes small. A large SWRC coefficient that results in slow rates of increase in degree of saturation affects the reduction in safety factor to be slow (Figure 13(d)).”
What is the criterion of the division of 12 zones? As you divide the whole area into 12 zones, then the number of zone should be added into the Table I.	First of all, we grouped sampling points where soil properties (i.e., unit weight, cohesion, internal friction angle, saturated hydraulic conductivity, and soil classification) were similar, and then the watersheds where sampling points belonging to the

	same group were combined to create a zone. As described in the "Study area" section, the study area consists of the same geological system (biotite gneiss). Thus, we used only the soil properties and watershed to classify zones. We revised the following sentences in Lines 274–276. *"We grouped the 37 sampling points where soil properties were similar and divided Halmidang Mountain into twelve zones (i.e., Zones 1 through 12) based on watersheds to which the groups of sampling points belong (see Figure 6)."* *Figure 4 was changed to Figure 6 in a revised manuscript. We added the number of zone in Table 2. *Table 1 was changed to Table 2 in a revised manuscript.
In the figure 3, the landslide occurs at 14:00. All or several the landslides happened at that time? Please support detailed information.	As we described in Lines 86–88, debris flows occurred along 21 watersheds between 13:00 and 15:00 on July 27, 2011, that were transformed from shallow slope failures. We added the following sentence in Line 88–89. *"We assumed an occurrence time of slope failures to be 14:00 on July 27, 2011 to simplify analyses."*
Table I, please check the unit and the value of γ_t and γ_d. The detailed information of all samples should be added.	We corrected values of γ_t and γ_d in Table 2. Considering that the information of all samples were not directly used for analyses in this study, we can provide it as a supplementary file.
Table II, please define the α, n and m.	While we responded to reviews from Referee #1, we applied k_{ss}, β_{d}, β_{w}, k_p, and a (Hu et al., 2013) for van Genuchten SWRC instead of a, n, and m. We added definitions of them in the footnote of Table 3. *Table 2 was changed to Table 3 in a revised manuscript.
Please zoom in two panels in Figure 5.	We corrected ranges of matric suction in two panels in Figure 7 from 0.01–1000 kPa to 0.1–100 kPa to zoom in the existing panels.

	*Figure 5 was changed to Figure 7 in a revised manuscript.