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 the insightful comments which truly helped enrich the manuscript. In the revised manuscript, we have clarified contributions of the manuscript. We have also applied the changed coupled hydro-mechanical model considering deformation-dependent water retention behavior with hydraulic hysteresis. For the comments raised by the reviewers, we have provided the point by point responses.

Referee #1's Comments	Responses
The research lacks novelty and has significant shortcomings with regard to the methodology and fails to impress upon the reader the need for such a complex undertaking instead of the traditional single-phase modelling at a regional scale.	We revised the following sentences in Lines 49–64 to complement 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. *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.*"
The use of the Kozeny-Carman equation (16) to link the volume changes in unsaturated soil with the variation of saturated hydraulic conductivity (ks) doesn't seem reasonable. The Kozeny-Carman equation is used to roughly predict the vertical saturated hydraulic conductivity for homogenised soils. As far as I am aware Chapuis and Aubertin (2003) or any other studies have not tested the equation to model volume change behaviours like swelling or collapse under saturated or unsaturated conditions. Whilst procedures to measure the volume change in unsaturated condition exists, the quantification of corresponding changes in hydraulic conductivity owing to the volume changes under rainfall	Several previous studies have used Kozeny–Carman equation incorporated in coupled hydro-mechanical models to compute the saturated permeability varied depending on porosity (e.g., Chapuis and Aubertin, 2003; Cho, 2016a; Kim et al., 2016; Kim et al., 2018). Changes in hydraulic conductivity owing to volume changes under rainfall infiltration have not exactly quantified, but it is clear that variations in void of soil affect permeability (Hu et al., 2011), and Hu et al. (2013) and Hu et al. (2018) have applied an equation to predict the permeability of deformable unsaturated soils. We also applied their equation incorporated in the coupled hydro-mechanical model. We revised the following sentences in Lines 190–198. "*Chapuis and Aubertin (2003), Cho (2016a), Kim et al. (2016), and Kim et al. (2018) have used Kozeny–Carman equation incorporated in coupled hydro-mechanical models to compute the saturated*

infiltration is a task yet to be accomplished. The paper also doesn’t explain how the Kozeny-Carman equation for saturated hydraulic conductivity is used to model effective stress changes and the subsequent variations in unsaturated hydraulic conductivity under rainfall infiltration. In light of the above shortcoming, the reviewer thinks the review of the results presented in the paper as of now would be a fruitless exercise.	*permeability which depends on porosity. Hu et al. (2013) and Hu et al. (2018) have applied Eq. (20) to predict the permeability of deformable unsaturated soils, which depends on changes in porosity and void ratio. Because changes in permeability of the soil deformed during rainfall infiltration are not considered in FLAC, we programmed Eq. (20) to be applied during infiltration analysis using an in-built programming language (FISH).* $k(e) = \frac{k_0}{{n_0}^2 exp(2k_p e_0)} n^2 exp(2k_p e)$ *(20)* *where* k_0 *is the initial permeability,* n_0 *is the initial porosity,* k_p *is the parameter involved in Eq. (3), and* e_0 *is the initial void ratio.*” We added the following sentences in Lines 199–205 to describe the scheme of a coupled hydro-mechanical model and how Eq. (20) was incorporated in the model. “*The coupled hydro-mechanical model consists of the fluid flow, mechanical, and water retention model loops. The fluid flow loop evaluates fluid flows from pressure gradients and changes in saturation and pore pressure due to unbalanced flows, based on from Eq. (7) to Eq. (13). The mechanical loop evaluates total stress depending on velocities, coordinates, and generation of pore pressure due to mechanical volume strain, based on from Eq. (14) to Eq. (19). The water retention model loop updates saturation and permeability that depend on mechanical volumetric change and generation of pore pressure, based on from Eq. (3) to Eq. (6) and Eq. (20). The stress state sequentially updated from the modified water retention behavior is applied to the next time step for the fluid flow loop.*”
The authors have not clearly explained how the two-dimensional model for	We added the following sentences in Lines 207–214 in section 4.1 to describe how to apply a coupled

seepage analysis (FLAC) has been applied at a regional scale. Has the subsurface-flow routing from different grid cells been considered? Also, any attempts at validation cannot be seen (e.g. field-based monitoring, streamflow data from gauge stations, etc.).	hydro-mechanical model for infiltration analyses at a regional scale. “*We applied the coupled hydro-mechanical model for simulations of rainfall infiltration to the independent 2D infinite slope model considering slope angles from different cells of the slope raster computed from the DEM in the study area. The depths from ground surfaces to slope failure surfaces observed during our field investigation are generally shallow and comparable with a range of 1–3 m associated with Korea (Kim et al., 2004). We set a uniform soil depth and a length of an infinite slope to be 2 m and 10 m, respectively, and applied the soil properties obtained from field investigations. Finally, saturations and pore pressures of wetting and non-wetting fluids (water and air) could be computed at all area of the infinite slope for a period of 22 hours from starting the simulations.*” We added the section 5.1 (Lines 232–263) for validation of the coupled hydro-mechanical model using the experimental results obtained from Liakopoulos (1964).
Did the authors use the effective stress estimated during the hydro-mechanical coupled seepage analysis in FLAC in the assessment of the factor of safety? Please provide a detailed explanation in section 4.2.	We added the following sentences in Lines 227–230 in section 4.2 to describe how to determine safety factors. “*We evaluated slope stability of infinite slope models for a period of 22 hours based on Eq. (20) utilizing the variations in saturations and pore pressures of water and air with time simulated from the coupled hydro-mechanical model. The minimum safety factors of infinite slope models were finally determined to be safety factors of different cells of the GIS-based topography of the study area.*”
It is difficult to follow the motivation of the authors in conducting the two-phase coupled hydro-mechanical based	We revised the sentences in Lines 49–64 to complement contributions of this work, as shown in the response to the first comment.

infiltration modelling at a regional scale. No information could be found in the paper with regard to the volume change behaviour of soils from Central Korea under unsaturated conditions (soil volume changes under wetting and drying). This is a fundamental issue the authors need to sort out before attempting to model at any scale. Also, under circumstances of volume change, authors would require to carry out SWCC corrections for volume change as well.	Volume change of unsaturated soils depends on changes in matric suction and net normal stress (Matyas and Radhakrishna, 1968; Fredlund and Rahardjo, 1993). Soils in Korea would also be expected to follow this relationship among them. We added the following sentence in Lines 39–43 to describe why the volume change behavior of unsaturated soils should be used. "*Considering that volume of unsaturated soils changes depending on matric suction and net normal stress (Matyas and Radhakrishna, 1968) and relationship among them can be considered to make the constitutive equation for volumetric strain of unsaturated soils (Fredlund and Rahardjo, 1993), a coupled hydro-mechanical model considering the volume change behavior can be applied to simulate hydraulic processes in unsaturated soils.*" We applied the deformation-dependent water retention curve model (Hu et al., 2013; Hu et al., 2016) to consider both volume change of unsaturated soils and water retention curve hysteresis, as shown in the following sentences in Lines 127–146, and we corrected SWRC model parameters in Table 3. "*The hydraulic hysteresis reflects different hydraulic states and hydraulic paths, and the saturation of the wetting fluid for deformable soils depends on the soil skeleton deformation as well as matric suction (Hu et al., 2013; Hu et al., 2016). The water retention behavior is classified into two groups, the main wetting and drying surfaces and the scanning curves. Eq. (1) can be replaced by Eq. (3), which defines a bounding surface (wetting or drying) considering the hysteretic water retention behavior for deformable soils subjected to mechanical and hydraulic loading.*

	$S_{e,\gamma}(\psi,e) = \left[\{\beta_\gamma exp(k_p e)\psi\}^{\frac{1}{1-a}} + 1\right]^{-a}, \ \gamma = w, d \qquad (3)$ *where* β_γ *is the air entry value (for main drying surface,* $\beta_\gamma = \beta_d$*, and for main wetting surface,* $\beta_\gamma = \beta_w$*),* k_p *is the model parameter, and* e *is the void ratio.* *Hu et al. (2013) considered the incremental effective saturation associated with scanning zones during movement of a soil state, expressed by Eq. (4). Integrating Eq. (4) from* $S_{e,n}$ *to* $S_{e,n+1}$*,* ψ_n *to* $\psi_{n+1}\ (= \psi_n + d\psi_n)$*, and* e_n *to* $e_{n+1}\ (= e_n + de_n)$*, Eq. (6) can be obtained to compute the updated trial effective saturation (*$S_{e,n+1}^{trial}$*).* $dS_e = -S_e\left(1 - {S_e}^{-1/a}\right)\left(k_{ss}\frac{d\psi}{\psi} + k_{se}de\right) \qquad (4)$ $\begin{cases} \frac{\partial lnS_e}{\partial ln\psi} = -k_{ss}\left(1 - {S_e}^{1/a}\right) \\ \frac{\partial lnS_e}{\partial e} = -k_{se}\left(1 - {S_e}^{1/a}\right) \end{cases} \qquad (5)$ $S_{e,n+1}^{trial} = \left[1 - \frac{(\psi_{n+1})^{k_{ss}/a} exp\left(\frac{k_{se}}{a} e_{n+1}\right)}{(\psi_n)^{k_{ss}/a} exp\left(\frac{k_{se}}{a} e_n\right)}\left(1 - {S_{e,n}}^{-1/a}\right)\right]^{-a} \qquad (6)$ *where* k_{ss} *and* k_{se} *are the slopes of the asymptotes for the scanning curves in the* $lnS_e - ln\psi$ *and* $lnS_e - e$ *planes, respectively.* *The following procedure is required to determine the updated saturation (*$S_{e,n+1}$*):* *If* $S_{e,n+1}^{trial} < S_{e,d}(\psi_{n+1}, e_{n+1})$ *and* $S_{e,n+1}^{trial} > S_{e,w}(\psi_{n+1}, e_{n+1})$ *then* $S_{e,n+1} \leftarrow S_{e,n+1}^{trial}$ *; else if* $S_{e,n+1}^{trial} \geq S_{e,d}(\psi_{n+1}, e_{n+1})$ *then* $S_{e,n+1} \leftarrow S_{e,d}(\psi_{n+1}, e_{n+1})$ *; else* $S_{e,n+1}^{trial} \leq S_{e,w}(\psi_{n+1}, e_{n+1})$ *then* $S_{e,n+1} \leftarrow S_{e,w}(\psi_{n+1}, e_{n+1})$.”
Another drawback is the lack of description with regard to the field mapped landslide characteristics, evidence from sites in all zones with regard to soil profiles (single or several different layers) and soil depth especially when field investigations were carried out (mentioned in Section 3). Please provide necessary details.	We added the following sentences in Lines 104–109 in Section 3 to supply additional information about landslides in the study area and observations during field investigations. “*From the slope failures, a total of 21 debris flows were transformed with a total debris flow spreading area of approximately 94,000 m*^{2}*. Areas and distances of debris flow spreading ranged from 1,100 to 19,600 m*^{2} *and from 90 to 580 m,*

	respectively. We checked the accuracy of the landslide inventories by comparing some of them with actual slope failure sites during our field investigations. Figure 2(b) shows the slope failure initiation sites we observed. Failure surfaces were within depths to weathered rocks up to which soils consisted of a single layer. Depths from ground surfaces to slope failure surfaces were generally shallow within a range from 1.3 to 2.1 m.”
Vanapalli et al. (1996) used two approaches to calculate the shear strength. The first approach was to use a dimensionless number "normalised area of water with k as a fitting parameter" and the second approach was to use a normalised degree of saturation (defined as effective saturation in this paper) wherein the residual degree of saturation needs to be estimated. The authors in this study have substituted Bishop’s matric suction coefficient with the saturation of a wetting fluid variable (Equation 12 and Equation 14). Could the authors explain the basis for equating the degree of saturation (instead of an effective saturation) of a wetting fluid with the Bishop’s matric suction coefficient?	Some previous studies have used degree of saturation to be the matric suction coefficient (χ) in Bishop’s effective stress equation (e.g., Chateau and Dormieux, 2001, 2002; Cho, 2016b; Hu et al., 2018; Zhang et al., 2018). We revised the following sentence in Lines 176–179. “*The matric suction coefficient (χ) in Bishop’s effective stress equation can be substituted by the saturation of a wetting fluid (S_w) (Chateau and Dormieux, 2001, 2002; Cho, 2016b; Hu et al., 2018; Zhang et al., 2018), and Pham et al. (2019) reported that critical points computed from effective stress utilizing the S_w were close to saturated critical state line with large correlations statistically evaluated.*”
The authors have focused more on the modelling aspect with advanced two-phase modelling at the regional scale and did not worry much about the variability in input data which clearly will influence the safety factor values. It is recommended that such a study (sensitivity analysis) be undertaken in the region. Also, could the authors explain why only watershed criteria was	We added Figure 13 and the following sentences in Lines 416–430 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*

used in creating the zones? Why wasn't geological information used? Please explain in detail.	*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)).*” As described in the "Study area" section, the study area consists of same geological system (biotite gneiss). Thus, we used only the watershed to classify zones.

The reasoning for the selection of a 10-m DEM is not clear (Section 3). Why is channelisation important for slope stability analysis? I can understand its importance in debris flow modelling. Please explain by also including information with regard to the size of landslides mapped.	We corrected the following sentence in Lines 95–98 to simplify descriptions about why we applied a 10-m DEM. "*Considering the cell size of digital elevation model (DEM) used in previous studies which have evaluated physically based models for predicting landslides at a regional scale (e.g., Park et al., 2016; Salvatici et al., 2018; Park et al., 2019), we utilized the DEM with a cell size of 10 m.*" We added the following sentences in Lines 104–109 to supply additional information about landslides in the study area. "*From the slope failures, a total of 21 debris flows were transformed with a total debris flow spreading area of approximately 94,000* m^2*. Areas and distances of debris flow spreading ranged from 1,100 to 19,600* m^2 *and from 90 to 580 m, respectively. We checked the accuracy of the landslide inventories by comparing some of them with actual slope failure sites during our field investigations. Figure 2(b) shows the slope failure initiation sites we observed. Failure surfaces were within depths to weathered rocks up to which soils consisted of a single layer. Depths from ground surfaces to slope failure surfaces were generally shallow within a range from 1.3 to 2.1 m.*"