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1	A FEM-MPM Hybrid Coupled Framework Based on Local Shear Strength Method for
2	Simulating Rainfall/runoff-induced Landslide Runout
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22		Highlights
23		
24	1.	A local shear strength method is proposed for evaluating the variation of the shear strength for
25		each soil material point.
26	2.	A FEM-MPM hybrid coupled framework is proposed to simulate rainfall/runoff triggered
27		landslide runout in unsaturated slopes.
28	3.	Simultaneous analysis of runoff, seepage, and landslide runout within a small catchment scale is
29		successfully performed.
30		

#### 31 Abstract

32 Limited by the independence and its defects of each general software package, simultaneous analysis 33 of runoff, seepage, and large-deformation analysis is still an inevitable challenge. Generally, one of 34 seepage, landslide-related large-deformation, and runoff is ignored or indirectly assessed during 35 unsaturated soil landslide runout simulation. To provide a brand new solution, this paper declares a 36 local shear strength (LSS) method to evaluate rainfall/runoff-induced reduction of the unsaturated soil 37 shear strength. After that, a hybrid coupled hydro-mechanical framework is proposed to simulate 38 rainfall/runoff-induced landslide runout within an unsaturated soil slope. The decrease in local shear 39 strength corresponding to the decrease in matric suction is defined by shifting the Mohr-Coulomb 40 (M-C) failure envelope towards compressive stress space during rainfall/runoff infiltration. Based on 41 the proposed local shear strength method, the variable matric suction obtained from the bidirectionally 42 coupled runoff and seepage analysis in FEM is unidirectionally transferred to the variable local shear 43 strength for each soil material point in MPM (i.e., this is a FEM-MPM hybrid coupled model). Then, 44 the correctness of the proposed hybrid coupled hydro-mechanical framework is effectively verified by 45 a hypothetical homogeneous slope model. The results show that the slope stable/unstable state 46 simulated by the proposed hybrid coupled hydro-mechanical framework has a good consistency with 47 that simulated by the shear strength reduction technique (SSRT) and limit-equilibrium method (LEM). Afterward, combined with a case study of a natural landslide in Hokkaido, Japan, it is proved to be 48 49 effective for simulating landslide runout subjected to rainfall/runoff infiltration by using the proposed 50 hybrid coupled hydro-mechanical framework in an unsaturated soil slope.

*Keywords*: Local shear strength method; Material point method; Rainfall/runoff-induced landslide
 runout; Finite element method; Unsaturated soil slope

53

#### 54 **1. Introduction**

55 In many mountainous regions, rainfall/runoff is considered to be the main cause triggering 56 landslides/slope failures. With the intensification of global and regional climate change, extreme 57 rainfall events and huge flooding have occurred frequently in recent years (Paerl et al., 2020; Wei et 58 al., 2020). The decrease in matric suction in the unsaturated zone caused by rainwater infiltration 59 under torrential rain is considered the main cause of the landslide/slope failure initiation (Zhu et al., 60 2020). After the landslide/slope failure occurs, the collapsed soil moves downward, namely landslide 61 runout, threatening the lives and properties of residents living downslope, especially those living near 62 the foothills. Therefore, it is of great social and economic value to study the landslide runout distance, 63 reasonably install the disaster prevention measures, and set the evacuation area. Many scholars have 64 made great efforts to develop numerical methods for simulating landslide runout, e.g. Discrete 65 Element Method (DEM) (An et al., 2021), Discontinuous Deformation Analysis (DDA) (Shi, 1989; 66 Peng et al., 2020), and Material Point Method (MPM) concurrently researched and operated by 67 several groups (Müller and Vargas, 2019; Acosta et al., 2021; Sun et al., 2021; Ying et al., 2021). 68 Among them, DEM and DDA consider the geo-material as discrete blocks connected by spring units. 69 Though DEM and DDA are recognized as having the advantages to simulate the cracking behaviors 70 of continuous media or model the contact, collision, slipping, and movement of discretely stacked 71materials, these two methods also suffer from low convergence, low accuracy, high calibration

72	requirements, and high computational costs. Besides, runoff and seepage analysis are still considered
73	as the main limitations of them. Furthermore, a depth-integrated continuum method that uses
74	continuum to model landslide mobility is recently developed by Iverson et al. (2015), Ouyang et al.
75	(2017), and Ouyang et al. (2019). In this method, integrated by the Navier-Stokes equations and flow
76	depth, the mass and momentum equations are solved by using the finite difference method. Apart
77	from these, another method, MPM, is also getting continued attention since it was first formulated by
78	Sulsky et al. (1994), as it avoids the problem of mesh distortion problems in the FEM and shows
79	higher computing efficiency compared with DEM and DDA. In MPM, the material bodies are
80	represented by a large number of material points. The physical information (velocity, acceleration,
81	mass, etc.) is stored in those material points. During the computational process of MPM, the physical
82	information will be repeatedly converted between the background grid and the material points to form
83	a link between the physical information and the spatial position.
84	The single-phase (solid phase) MPM has been maturely adopted to simulate landslides without
85	considering hydrology. For example, Sun et al. (2015) validated the applicability of the MPM in
86	simulating runout according to the comparative results of experiments and simulations of a simple
87	landslide example. Woo and Rodrigo (2018) presented a generalized interpolation MPM to get higher
88	computational accuracy and efficiency of MPM. Recently, MPM has also been developed to capture

the rapid landslide behavior in the form of a soil-water mixture. The porous solid phase, pore water phase, and/or pore air phase are characterized by using two or more Lagrangian layers, i.e., two-phase MPM or multi-phase MPM (e.g., Soga et al., 2016; Liang et al., 2020; Lei et al., 2021). However, it is worth noting that the objects of the above researches are mainly rainfall-induced landslides/slope

93	failures in saturated soil or unsaturated soil. The runoff analysis with changes in water depth is
94	neglected since it is considered as one of the fundamental challenges when using either single-phase
95	and two-phase MPM or multi-phase MPM. From the view of the coupling process of runoff and
96	seepage, and the variation of matric suction in unsaturated soil, the traditional numerical method,
97	FEM, has more advantages than other methods. Further, it has been widely used in general
98	commercial software packages, which are designed to analyze runoff and seepage. For example,
99	COMSOL Multiphysics (COMSOL Multiphysics, 2018) and GEO-SEEP/W (GeoStudio International,
100	2007). Therefore, proposing a FEM-MPM coupled computational framework will give full play to
101	their respective advantages in the coupled simulation of runoff, seepage, and landslide runout.
102	Consequently, the objective of this study was to establish a coupled hydro-mechanical framework
103	to simulate landslide runout triggered by rainfall/runoff infiltration within an unsaturated slope. To
104	achieve this goal, this study firstly proposes a local shear strength method for defining the variation of
105	the local shear strength induced by the rainfall/runoff infiltration for each soil material point. Then,
106	based on the proposed local shear strength method, a hybrid coupled hydro-mechanical framework is
107	developed. In the hybrid coupled hydro-mechanical framework, the seepage behavior is captured by
108	bidirectionally coupled runoff and seepage analysis with the FEM. Then, the variable matric suction
109	obtained from FEM is unidirectionally transferred to the variable local shear strength of each soil
110	material point in MPM by using the local shear strength method. The resulting slope failure behavior
111	is analyzed by the MPM. Thus, a FEM-MPM hybrid coupled model is established. Finally, through a
112	validation model and a case study of a natural slope, the results proved that the proposed FEM-MPM

113 hybrid coupled model is effective for coupled simulating runoff, seepage, and large-deformation

114 problems, such as rainfall/runoff-induced landslide runout within an unsaturated slope.

#### 115 2. Definition of local shear strength for each unsaturated soil material point

- 116 The saturated soil shear strength for each material point is defined by the Mohr-Coulomb (M-C) 117 failure criterion,
- 118

$$\tau_f = c' + \sigma' \tan \phi' \tag{1}$$

119 where,  $\tau_f$  is the shear strength (kPa); c' is the effective cohesion (kPa);  $\phi'$  is the effective internal 120 friction angle (°);  $\sigma'$  is the effective normal stress on failure plane (kPa).

121 In reality, the soil above the phreatic surface is in an unsaturated state. In this state, the soil will 122 have higher shear strength than in a saturated state. Currently, the well-known method is to describe 123 the unsaturated soil behavior by using Bishop's effective stress concept (Bishop, 1959),

124 
$$\sigma' = (\sigma - u_a)_f + \chi (u_a - u_w)_f , \ \chi = \frac{S_e - S_r}{1 - S_r}$$
(2)

## 125 where, $u_a$ is pore air pressure (kPa), $u_w$ is pore water pressure (kPa); $\sigma$ is total normal stress (kPa); $\chi$ is

126 effective stress parameter;  $S_e$  is effective degree of saturation;  $S_r$  is residual degree of saturation.

127 The unsaturated soil shear strength is also defined by Fredlund et al. (1978),

128 
$$\tau_f = c' + (\sigma - u_a)_f \tan \phi' + (u_a - u_w)_f \tan \phi^b$$
(3)

129 where, 
$$\phi^{b}$$
 is the angle indicating the rate of increase in shear strength relative to the matric suction  
130  $(u_{a}-u_{w})_{f}$ .

Eqs. (2) and (3) present proper compliance with in-door test results and have been widely used (Vanapalli et al., 1996). Vanapalli et al. (1996) discussed the applicability of the above two shear strength models in geotechnical engineering practice and built the relationship between the two 134 models,

135 
$$\chi = \frac{\tan \phi^b}{\tan \phi'} \tag{4}$$

136 Therefore, the unified equation form can be written as,

137 
$$\tau_f = c' + (\sigma - u_a)_f \tan \phi' + (u_a - u_w)_f \chi \tan \phi'$$
(5)

138 which also can be written as,

$$\tau_f = \underbrace{\left[c' + (u_a - u_w)_f \chi \tan \phi'\right]}_{c'_f} + (\sigma - u_a)_f \tan \phi' \tag{6}$$

140 where,  $c_f$  is the intercept at a specific matric suction,  $(u_a - u_w)_f$ , (kPa).

141 Conventionally, the M-C failure envelope is fixed for the entire slope during rainfall infiltration. 142 Changes in pore water pressure caused by rainfall/runoff infiltration only affect the scaling and 143 translation of the stress circle. Meanwhile, at present, describing the difference in matric suction 144 induced by runoff of various material points is still a potential challenge of the MPM. Therefore, 145according to Eq. (6), the variation of local shear strength for each material point in MPM can be 146 described by including matric suction in the cohesion intercept. The new cohesion intercept,  $c_{i}$ , is 147 called the total cohesion intercept. This provides a feasible way to define the variation of matric 148 suction and local shear strength for each soil material point in the unsaturated region, as cohesion is one 149 of the material properties that must be assigned during the modeling process. Eq. (6) suggests that a 150 decrease in local shear strength (the intercept of the M-C failure envelope decrease) corresponding to 151 a decrease in matric suction during rainfall/runoff infiltration is defined by shifting the M-C failure 152envelope towards compressive stress space as illustrated in Fig. 1. Consequently, the influences of 153matric suction changes on the variation of the local shear strength of each soil material point in the

unsaturated region can be considered by using the proposed local shear strength method as shown in

#### 155 Fig. 1.







Fig. 1. Local shear strength (LSS) for each unsaturated material point.

#### 158 **3.** Hybrid coupled hydro-mechanical framework and governing equations

Based on the proposed local shear strength method, this section firstly proposes a hybrid coupled hydro-mechanical framework of FEM and MPM to simulate runoff, seepage, and large-deformation of the unsaturated soil slope. Then, the governing equations used in the runoff model, seepage model,

- 162 and soil mechanics model are presented.
- 163 3.1 Hybrid coupled hydro-mechanical framework

164 During a rainstorm or torrential rain, the generation of runoff has a significant impact on soil 165 moisture, ground surface erosion, and landslides. Meanwhile, in unsaturated soils, the variation of 166 volumetric water content affects matric suction, which thereby affects local shear strength. It also 167 affects the self-weight and stress distribution. Therefore, the effects of runoff on the soil moisture 168 changes, and the effects of soil moisture changes on local shear strength and self-weight of 169 unsaturated soil are considered in the coupled hydro-mechanical framework. In the hybrid coupled 170hydro-mechanical framework, the runoff and seepage are simulated by using the PDEs (partial 171differential equations) module in the FEM software, COMSOL Multiphysics (COMSOL Multiphysics, 1722018), while the large-deformation of the landslide is simulated by using MPM3D (an MPM code that 173was programmed by the group led by Prof. Zhang Xiong at Tsinghua University, 174http://comdyn.hy.tsinghua.edu.cn/english/mpm3d). The coupled hydro-mechanical framework is 175shown in Fig. 2. The runoff model and seepage model in FEM are bidirectionally coupled through the 176 interaction between surface water and groundwater (infiltration and exfiltration). The water depth 177calculated from the runoff model is applied to the seepage model as the water head boundary 178condition. The inflow velocity (infiltration) and outflow velocity (exfiltration) calculated from the 179 seepage model is returned to the runoff model as the source of water. The coupling process is 180 described in detail elsewhere (Zhu et al., 2020). The FEM analysis and MPM analysis are 181 unidirectionally coupled in two means: (1) the influence of changes in soil moisture content (FEM 182 output) on self-weight (MPM input) is taken into account in the elastoplastic model, and (2) the 183 influence of matric suction (FEM output) on the local shear strength (MPM input) is considered by 184 using the local shear strength method. It is worth noting that as shown in Fig. 2, the proposed 185 FEM-MPM coupled model is not a fully coupled model but a hybrid coupled model. Runoff and 186 seepage analysis is bidirectionally coupled through infiltration and exfiltration in the FEM analysis, 187 while the FEM analysis provides inputs to the MPM analysis, meaning that this process is 188 unidirectionally coupled. Furthermore, under the proposed framework, during the long-term coupled 189 runoff and seepage analysis, it is assumed that the deformation of the slope is not considered because 190 the slope is remaining stable at this time. While during the large-deformation analysis when the 191 landslide occurs, the change of seepage force, shear strength, and pore water pressure are neglected as

192 slope failure is a quickly triggered and rapidly developing geological hazard. Therefore, these



193 assumptions are the limitations of the proposed coupled hydro-mechanical framework.



195

Fig. 2. Hybrid coupled hydro-mechanical framework of FEM and MPM.

196 3.2 Governing equation for runoff analysis

197 Runoff analysis is governed by the diffusion wave (DW) equation as shown in Eq. (7) (Weill 198 et al., 2009; Zhu et al., 2020),

 $\frac{\partial h}{\partial t} - \nabla \left( \frac{h^{5/3}}{n_m \sqrt{|S|}} \nabla(H) \right) = R - I$ 199 (7)

200 where, I is infiltration/exfiltration rate (m/s); t is time (s);  $n_m$  is Manning's roughness coefficient 201  $(s/m^{1/3})$ ; h is runoff depth (m); H is water surface elevation (m); R is rainfall intensity (m/s); S is water 202 surface gradient, which can be replaced by slope gradient due to the small difference between them 203 (Weill et al., 2009).

204 3.3 Governing equation for seepage analysis

205 Seepage analysis is governed by the equation proposed by Richards (1931) which can be 206 expressed as follows,

207 
$$\nabla \cdot \left[k_s \ k_r \cdot \nabla \left(H_p + z\right)\right] + Q_w = \left[C_m + S_e S_c\right] \frac{\partial H_p}{\partial t}$$
(8)

where,  $Q_w$  is sink and source of water (s<sup>-1</sup>), which is related to *I*;  $k_s$  is saturated hydraulic conductivity (m/s);  $C_m$  is specific moisture capacity (m<sup>-1</sup>);  $k_r$  is relative hydraulic conductivity;  $S_c$  is specific storage coefficient (m<sup>-1</sup>);  $H_p$  is pressure head (m);  $S_e$  is the effective degree of saturation; *z* is the elevation (m). The relationship in  $C_m$ ,  $S_e$ ,  $k_r$ ,  $\theta$ , and  $H_p$  in unsaturated soil can be calculated by  $\theta_s$ ,  $\theta_r$ , and the vG parameters, *a*, *n*, *m*, and *l* (van Genuchten, 1980).

213 
$$\theta = \theta_r + S_e(\theta_s - \theta_r) \tag{9}$$

214 
$$S_e = \frac{1}{\left[1 + \left(aH_p\right)^n\right]^m} , \ m = 1 - \frac{1}{n}$$
(10)

215 
$$C_m = \frac{am}{1-m} (\theta_s - \theta_r) S_e^{\frac{1}{m}} (1 - S_e^{\frac{1}{m}})^m$$
(11)

216 
$$k_r = S_e^{\ l} \left[ 1 - (1 - S_e^{\frac{1}{m}})^m \right]^2$$
(12)

## 217 3.4 Governing equations in MPM

218 In MPM. each computational step can be divided into three phases: initial phase, Lagrangian 219 phase, and convective phase as shown in Fig. 3 (Sun et al., 2015). In the initial phase, the physical 220 information stored in material points (e.g., locations, velocities, mass, etc.) is mapped on the 221 Lagrangian background grid to get the initial solution values. In the Lagrangian phase, the material 222 points move with the Lagrangian background grid and the global equations are solved within the 223 Lagrangian background grid. After that, the stored physical information is updated. In the convective 224 phase, the Lagrangian background grid is reset, while the stored physical information remains 225 unchanged.



227 Fig. 3. Three phases of one computational step of MPM (adapted from Sun et al. (2015)).

228 The governing equations of large-deformation analysis in MPM can be expressed as follows (Abe

229 et al., 2013):

230 
$$\frac{d\rho(\theta)}{dt} + \rho(\theta)\nabla \cdot \boldsymbol{\nu} = 0 \quad \text{(Conservation of mass)} \tag{13}$$

231 
$$\rho(\theta)\boldsymbol{a} = \nabla \cdot \boldsymbol{\sigma} + \rho(\theta)\boldsymbol{b}$$
 (Conservation of momentum) (14)

232 where,  $\rho(\theta)$  is soil-water mixture density (kg/m<sup>3</sup>) as a function of volumetric water content ( $\theta$ ); *a* is 233 acceleration vector (m/s<sup>2</sup>); v is velocity vector; b is body forces vector (m/s<sup>2</sup>);  $\sigma$  is stress tensor (kPa) 234

(m/s).

#### 235Validation of the proposed hybrid coupled hydro-mechanical framework 4.

236 To check the reliability of the hybrid coupled hydro-mechanical framework proposed in this study 237 for simulating unsaturated soil slope instability, a validation model is simulated by the FEM-MPM 238 hybrid coupled model compared with the other two commonly used methods: limit-equilibrium 239 method and shear strength reduction technique. In the validation model, the water supply (rainfall and 240 runoff) is not considered. The two side walls and bottom are impermeable to water. The groundwater 241 level (GWL) is assumed to be -5 m. Table 1 lists the soil properties used in the validation model. The 242 model size and boundary conditions are displayed in Fig. 4. The simulation results of the shear strength reduction technique are obtained from COMSOL, and the simulation results of the limit-equilibrium method are obtained from another commercial slope-stability software package







Fig. 4. Schematic diagram of the validation model.

248 The comparison of the simulation results calculated by shear strength reduction technique, 249 limit-equilibrium method, and the proposed FEM-MPM hybrid coupled model are shown in Fig. 5. 250Fig. 5(a) shows the slope in the stable state. Fig. 5(b) shows the slope in the critical state. Fig. 5(c) 251shows the slope in the failure state. In each sub-figure (Fig. 5(a), Fig. 5(b), and Fig. 5(c)), Fig. 5(l) 252 displays the pressure head calculated by FEM. Fig. 5(II) displays the slip surface simulated by 253 limit-equilibrium method with the factor of safety (FOS). Fig. 5(III) displays the results simulated by 254 the shear strength reduction technique. Fig. 5(IV) displays the ultimate slope failure shape simulated 255by the proposed FEM-MPM hybrid coupled model. From Fig. 5(a), it is recognized that the slope 256simulated by the proposed FEM-MPM hybrid coupled model is stable. The FOS calculated by the 257 limit-equilibrium method (FOS=1.198) in Fig. 5(a)(II) and that calculated by the shear strength 258reduction technique (FOS=1.190) in Fig. 5(a)(III) are larger than 1.0. From Fig. 5(b), it is recognized 259 that the slope simulated by the proposed FEM-MPM hybrid coupled model is in a critical state. At the 260 same time, the FOS calculated by limit-equilibrium method (FOS=0.996) in Fig. 5(b)(II) and that

261	calculated by shear strength reduction technique (FOS=0.930) in Fig. 5(b)(III) are slightly less than
262	1.0, meaning that the slope is unstable under the pore water pressure distribution at this time. From
263	Fig. 5(c), it is recognized that the slope simulated by the proposed FEM-MPM hybrid coupled model
264	is failed. The FOS calculated by the limit-equilibrium method (FOS=0.567) in Fig. 5(c)(II) and that
265	calculated by shear strength reduction technique (FOS=0.590) in Fig. 5(c)(III) are much less than 1.0.
266	From Fig. 5(a), Fig. 5(b), and Fig. 5(c), it indicates that the slope stable/unstable state simulated by
267	the proposed FEM-MPM hybrid coupled model is consistent with that calculated by the
268	limit-equilibrium method and the shear strength reduction technique. The similar slip surface shapes
269	and stable/unstable state calculated by the proposed FEM-MPM hybrid coupled model,
270	limit-equilibrium method, and shear strength reduction technique give a good verification of the
271	proposed FEM-MPM hybrid coupled model on simulating slope instability in unsaturated soil,
272	although the slip surface calculated by shear strength reduction technique is slightly shallower in Fig.
273	5(b) and Fig. 5(c). The main reason could be that the slip surface calculated by the shear strength
274	reduction technique is the initial slip surface. Due to the calculation of the shear strength reduction
275	technique is terminated due to non-convergence after the shallow layer is damaged, the development
276	process of the slip surface from the initial stage to the ultimate stage is not considered by the shear
277	strength reduction technique.

# Table 1 Soil properties used in the validation model.

Dry density, ρ <sub>s</sub> (kg/m <sup>3</sup> )	Effective cohesion, c'(kPa)	Effective internal friction angle, $\phi'$	Young's modulus, <i>E</i> (MPa)	Poisson's ratio, v
1695	0 and 10	20 and 30	50	0.3
Saturated hydraulic	Saturated vol. water	Residual vol. water	vG	vG
conductivity, $k_s$ (m/s)	content, $\theta_s (m^3/m^3)$	content, $\theta_r (m^3/m^3)$	parameter, $\alpha$	parameter, <i>m</i>





Fig. 5. Numerical results calculated from limit-equilibrium method, shear strength reduction technique, and FEM-MPM hybrid coupled model. (a) Stable state; (b) Critical state; (c) Failure state. In each sub-figure, (I) pressure head calculated by FEM, (II) slip surface with FOS simulated by limit-equilibrium method, (III) slip surface with FOS simulated by shear strength reduction technique;

286 (IV) ultimate slope failure shape simulated by FEM-MPM hybrid coupled model.

#### **5.** Natural landslide simulation by the proposed FEM-MPM hybrid coupled model

288 5.1 Numerical model and soil properties

In 2016, typhoon No.10 hit Northern Japan at the end of August. During this period, several serious landslides occurred, for example, at location 1 in Fig. 6. The landslide is located in the Hidaka mountains in Hokkaido, Japan. The maximum observed cumulative rainfall in three days (29<sup>th</sup>-31<sup>st</sup>) reached 488 mm as plotted in Fig. 7. The geological conditions of this site are dominated by metamorphic rocks and plutonic rocks that belong to the Hidaka metamorphic belt. It is mainly composed of medium-grained and massive granite containing biotite. The shallow part of the granite that penetrates the sedimentary rocks of the Hidaka metamorphic belt is being weathered, forming a layer of weathered residual soil about 10 m on the ground surface. Focus on the target area surrounded by the red dashed rectangle in Fig. 6, a three-dimensional (3D) model for runoff and seepage analysis was built as displayed in Fig. 8(a). Fig. 8(b) displays the cross-section at Location 1. Only one two-dimensional (2D) profile at Location 1 was simulated by the MPM model for large-deformation analysis. Fig. 8(c) displays the material points with the number of 10,487 within the 2D profile. More simulations of 2D profiles along the sliding direction are repetitive work, so they are not carried out in this study.



303 304

305

306

Fig. 6. Locations and performance of slope failure.







307

Fig. 8. (a) 3D numerical model of the target area; (b) Cross-section at Location 1; (c) Material
 points at Location 1.

310 In the 3D model, the geological composition information is shown in Fig. 8(a), and it is 311 considered that the embankment exists only at the exit of the valley and the thickness of the soil is 10 312 m. Soil properties are listed in Table 2. The parameters i.e. dry density  $(\rho_s)$ , saturated hydraulic 313 conductivity ( $k_s$ ), saturated volumetric water content ( $\theta_s$ ), effective cohesion (c'), and effective friction 314 angle ( $\phi$ ), Young's modulus (E), and Poisson's ratio (v) have been obtained from laboratory element 315 tests (Sato et al., 2017). The parameters for which no results of laboratory tests are available, i.e., 316 residual volumetric water content ( $\theta_r$ ) and van Genuchten parameters ( $\alpha$  and m) were estimated based 317 on the grain size curve of soil by using the software, SoilVision (SoilVision, 2018). SoilVision is 318 geotechnical database software that contains data on over 6,200 soil samples. It can be used to 319 estimate the missing characteristic values of the soil based on the grain size curve of the soil. The 320 initial GWL is set to -5.5 m considering historical measurements. According to the value for mountain 321 grassland recommended by the Japan Institute of Country-ology and Engineering (JICE), Manning's 322 coefficient value is set to  $0.3 \text{ s/m}^{1/3}$ .

Parameters	Dry density, ρ <sub>s</sub> (kg/m <sup>3</sup> )	Effective cohesion, c' (kPa)	Effective internal friction angle, $\phi$ ' (°)	Young's modulus, E (MPa)	Poisson' s ratio, v
Embankment	1695	0	37	50	0.3
Soil	1020	0	35	50	0.3
Weathered granite	2000	37	21	500	0.3
Parameters	Saturated hydraulic conductivity, k <sub>s</sub> (m/s)	Saturated volumetric water content, $\theta_s$ $(m^3/m^3)$	Residual volumetric water content, $\theta_r$ $(m^3/m^3)$	vG parameter, α (1/m)	vG paramet er, <i>m</i>
Embankment	1.12×10 <sup>-5</sup>	0.36	0.035	0.538	0.468
Soil	$1.40 \times 10^{-6}$	0.63	0.190	0.810	0.012
Weathered granite	3.47×10 <sup>-9</sup>	0.48	0.008	0.437	0.246

Table 2 Soil properties used for the FEM-MPM hybrid coupled simulation.

324 5.2 Simulation results of the natural landslide induced by runoff

325 The bidirectionally coupled runoff and seepage analysis are firstly done with FEM. The 326 simulation time (represented by T) is a total of 70 hours from 2016-08-28 20:00 to 2016-08-31 18:00. 327 The calculation step is set as an adaptive time-stepping scheme that means the COMSOL will 328 automatically adjust the calculation time in each step to meet the desired Relative Tolerance (0.001 in 329 this study). The results output time step is 1.0 hour. That is after every hour of the bidirectionally 330 coupled runoff and seepage analysis, the volumetric water content and matric suction obtained from 331 FEM analysis are transferred to the MPM model and used for updating the information of mass 332 self-weight and local shear strength stored in each soil material point. From trial simulations, it is 333 found that from 15 s after the start of the MPM analysis, the slope failure shape does not change 334 significantly even if the calculation time is greatly increased. Therefore, the total time (represented by 335 t) for a landslide runout simulation by MPM is set to 15 s and the calculation step is 0.2 s. Fig. 9 336 shows the distribution of time-dependent water depth in the target area. In Fig. 9, it can be identified that the overland water from the watershed is gathered at Location 1 since Location 1 is located at the exit of the valley. The water depth exceeds 0.2 m in the upstream area of Location 1, which is much larger than other parts of the highway. This was considered as the main cause of the landslide that occurred at Location 1.





Fig. 9. Time-dependent water depth distribution at Nissho Pass (a) at T=10 h; (b) at T=30 h; (c)

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346	The simulated water depth $(h)$ at the road center (Point A in Fig. 8(b), located on the road
347	surface), pore water pressure $(u_w)$ , and total cohesion intercept $(c_f)$ at an exploratory point (Point B in
348	Fig. 8(b), located at 1.0 m deep below the road surface) are plotted in Fig. 10. From Fig. 9 and Fig. 10,
349	it is identified that the generation of runoff is at 22 hours after the bidirectionally coupled runoff and
350	seepage analysis starts. After runoff is generated, there is a dramatic increase in $u_w$ and a sudden drop
351	of $c_f$ , meaning that the generation of runoff has a remarkable influence on the matric suction and
352	local shear strength of the embankment. Afterward, the matric suction gradually decreases to close to
353	zero, i.e., the pore water pressure $(u_w)$ gradually increases to close to zero (soil is nearly saturated),
354	causing a continuous decrease in total cohesion intercept $(c_f)$ of the embankment. The decrease in the
355	total cohesion intercept $(c_f)$ leads to the decrease in the local shear strength, which causes the
356	occurrence of the landslide. Fig. 11 shows the effective degree of saturation (Se) at different times. It
357	is recognized that the unsaturated soil lies above the saturated zone. The infiltration of rainwater
358	gradually saturates the soil on the surface layer, thus resulting in the size of the unsaturated zone
359	becoming smaller. It is also identified that after runoff is generated at T=22 h, the soil on the surface
360	layer becomes saturated at T=30 h in Fig. 11 and the saturated area gradually increases with time after
361	T=30 h.



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**Fig. 11.** Distribution of time-dependent effective degree of saturation at Nissho Pass (a) at T=0 h;

(b) at T=30 h; (c) at T=50 h; (d) at T=70 h.

365 Fig. 12 shows the distribution of effective plastic strain (EPS) and slope failure shape with large 366 deformation at 15 s in the landslide simulation. A new MPM analysis has been run for each time with 367 different matric suction and local shear strength outputted from FEM analysis. During the MPM 368 analysis, it is assumed that the matric suction and local shear strength for each point keep constant. 369 The above assumption can be considered reasonable since the calculation of MPM is completed in 370 only 15 seconds, which is a very short time so the change of matric suction and local shear strength is neglectable. From Fig. 12. it is recognized that the slope is stable before T=40 h due to a large size 371 372 unsaturated zone lies above the saturated zone (see Fig. 11). Though high matric suction causes a high 373 local shear strength of the embankment soil, with the infiltration of rainwater, the matric suction 374 gradually decreases, causing a continuous decrease in local shear strength of the embankment (see Fig. 375 10). Finally, the slope failure occurred at approximately 40 h (the highway was closed at the same 376 time as shown in Fig. 10) and reached its ultimate shape between 40 h and 50 h (slope failure was 377 complete). Therefore, this simulation has also shown the effectiveness of the proposed hybrid coupled 378 hydro-mechanical framework (FEM-MPM hybrid coupled model) to reproduce and/or predict the 379 rainfall/runoff induced slope failure in unsaturated soil, although the simulated slip surface is 380 shallower compared with the actual one as shown in Fig. 12. The main reason could be that after the 381 occurrence of the landslide, the development of the slip surface caused by the erosion of the newly 382 exposed ground surface by the surface water has not been considered. This needs to be further 383 investigated by considering the continuous erosion of runoff in the proposed FEM-MPM hybrid 384 coupled model, which is one of the limitations of this study currently.





386 Fig. 12. Distribution of effective plastic strain and slope failure shape with large deformations at

387

Nissho Pass.

#### 6. Discussions and conclusions

This paper proposes a local shear strength method for determining the variable local shear strength corresponding to the variable matric suction for each soil material point within a small catchment-scale unsaturated slope. The local shear strength method built a relationship between the variable local shear strength and the variable matric suction of each soil material point during rainfall/runoff infiltration by shifting the M-C failure envelope.

394 A hybrid coupled hydro-mechanical framework is proposed based on the local shear strength 395 method to solve rainfall/runoff induced landslide runout in unsaturated slopes. Based on the hybrid 396 coupled hydro-mechanical framework, a FEM-MPM hybrid coupled model is established. The 397 landslide analysis results suggest that the slope stable/unstable state simulated by the FEM-MPM 398 hybrid coupled model has a good consistency with the slip surface simulated by the limit-equilibrium 399 method and shear strength reduction technique. It is proved to be also reliable to simulate the actual 400 slope failure process to determine the occurrence time and location. Therefore, the proposed 401 FEM-MPM hybrid coupled model is proved to be applicable for simulating rainfall/runoff-induced 402 unsaturated soil landslide runout and has the potential to understand the location of landslide initiation 403 and the morphological evolution.

These findings indicate that the local shear strength method and hybrid coupled hydro-mechanical framework proposed in this study provide a feasible way to simulate rainfall/runoff-induced landslide runout in unsaturated soil slopes. It is of great significance to evaluate the landslides movement distance and reasonably recommend the installation of barrier structures to protect the lives and properties of residents living downslope. However, the internal 409 moisture changes and the dynamic support provided by the runoff during the movement of the 410 landslide are not considered in this study. These should be considered in the future assignments of this 411 study.

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#### 416 **Data Availability**

417 Weather station data used in this research can be downloaded from Japan Meteorological Agency

418 (http://www.data.jma.go.jp/gmd/risk/obsdl/index.php) and terrain information can be got from

419 Geospatial Information Authority of Japan (<u>https://www.gsi.go.jp/top.html</u>).

#### 420 **Declarations**

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## 425 **Competing Interests**

426 The authors have no relevant financial or non-financial interests to disclose.

#### 427 **References**

428	Abe, K., Soga	, K., Bandara,	S., 2013. N	Material poi	nt Method for	coupled h	ydromechanical	problems.
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- 429 Journal of Geotechnical and Geoenvironmental Engineering. 140(3), 04013033.
- 430 Acosta, J.L.G., Vardon, P.J., Hicks, M.A., 2021. Study of landslides and soil-structure interaction
- 431 problems using the implicit material point method. Engineering Geology. 285, 106043.
- 432 An, H., Ouyang, C., Zhou, S., 2021. Dynamic process analysis of the Baige landslide by the 433 combination of DEM and long-period seismic waves. Landslides. 18(5), 1625-1639.
- 434 Bishop, A.W., 1959. The principle of effective stress, Teknisk Ukeblad, Norwegian Geotechnical
- 435 Institute. 106(39), 859-863.
- 436 COMSOL Multiphysics. version 5.4, COMSOL Inc., Sweden, 2018.
- 437 Fredlund, D.G., Morgenstern, N.R., Widger, R.A., 1978. The shear strength of unsaturated soils.
- 438 Canadian geotechnical journal. 15, 313-321.
- 439 GeoStudio International. GEOSLOPE, Calgary, Alberta, Canada, 2007.
- 440 Iverson, R.M., George, D.L., Allstadt, K., et al., 2015. Landslide mobility and hazards: implications
- 441 of the 2014 Oso disaster. Earth and Planetary Science Letters. 412, 197-208.
- 442 Lei, X., He, S., Abed, A., Chen, X., Yang, Z., Wu, Y., 2021. A generalized interpolation material
- 443 point method for modelling coupled thermo-hydro-mechanical problems. Computer Methods in
- 444 Applied Mechanics and Engineering. 386, 114080.
- Li, X., Yan, Q., Zhao, S., Luo, Y., Wu, Y., Wang, D., 2020. Investigation of influence of baffles on
- landslide debris mobility by 3D material point method. Landslides. 17, 1129–1143.

- Liang, D., Zhao, X., Soga, K., 2020. Simulation of overtopping and seepage induced dike failure
  using two-point MPM. Soils and Foundations. 60(4), 978-988.
- 449 Müller, A., Vargas, E.A., 2019. Correction to: Stability analysis of a slope under impact of a rock
- 450 block using the generalized interpolation material point method (GIMP). Landslides. 16, 1063.
- 451 Ouyang, C., Zhou, K., Xu, Q., et al., 2017. Dynamic analysis and numerical modeling of the 2015
- 452 catastrophic landslide of the construction waste landfill at Guangming, Shenzhen, China.
  453 Landslides. 14(2), 705-718.
- 454 Ouyang, C., An, H., Zhou, S., et al., 2019. Insights from the failure and dynamic characteristics of two
- 455 sequential landslides at Baige village along the Jinsha River, China. Landslides. 16(7),
  456 1397-1414.
- 457 Paerl, H.W., Hall, N.S., Hounshell, A.G., et al., 2020. Recent increases of rainfall and flooding from
- 458 tropical cyclones (TCs) in North Carolina (USA): Implications for organic matter and nutrient
- 459 cycling in coastal watersheds. Biogeochemistry. 150(2), 197-216.
- 460 Peng, X., Yu, P., Chen, G., Xia, M., Zhang, Y., 2020. Development of a coupled DDA-SPH method
- 461 and its application to dynamic simulation of landslides involving solid-fluid interaction. Rock
  462 Mechanics and Rock Engineering. 53(1), 113-131.
- 463 Richards, L.A., 1951. Capillary conduction of liquids through porous mediums. Physics. 1(5),
  464 318-333.
- 465 Sato, A., Hayashi, T., Hayashi, H., Yamaki, M., 2017. On the geotechnical properties of decomposed
- 466 granite soil in Hokkaido. 57th Technical Report of Hokkaido Branch of Japanese Geotechnical
- 467 Society. 145-148. (in Japanese)

468

Shi, G.H., Discontinuous Deformation Analysis A New Numerical Model for the Static and Dynamics of Block Systems. Ph.D. Dissertation, Dept. of Civil Engineering, 1989.

- 470 Soga, K., Alonso, E., Yerro, A., Kumar, K., Bandara, S., 2016. Trends in large-deformation analysis
- 471 of landslide mass movements with particular emphasis on the material point method.
- 472 Géotechnique. 66 (3), 248-273.
- 473 SoilVision. version, 4.23. SoilVision Systems Ltd. Saskatoon, Saskatchewan, Canada, 2018.
- 474 Sulsky, D., Chen, Z., Schreyer, H.L., 1994. A particle method for history-dependent materials.
- 475 Computer Methods in Applied Mechanics and Engineering. 118(1-2), 179-196.
- 476 Sun, F., Wang, G., Zhang, L., Wang, R., Cao, T., Ouyang, X., 2021. Material point method for the
- 477 propagation of multiple branched cracks based on classical fracture mechanics. Computer
- 478 Methods in Applied Mechanics and Engineering. 386, 114116.
- 479 Sun, Y., Yang, J., Song, E., 2015. Runout analysis of landslides using material point method. Iop
- 480 Conference Series: Earth and Environmental Science. IOP Publishing. 26(1), 012014.
- 481 van Genuchten, M. Th., 1980. A closed-form equation for predicting the hydraulic conductivity of
- 482 unsaturated soils. Soil Science Society of America Journal. 44(5), 892-898.
- 483 Vanapalli, S.K., Fredlund, D.G., Pufahl, D.E., Clifton, A.W., 1996. Model for the prediction of shear
- 484 strength with respect to soil suction. Canadian geotechnical journal. 33(3), 379-392.
- Wei, K., Ouyang, C., Duan, H., Li, Y., Chen, M., Ma, J., An, H., Zhou, S., 2020. Reflections on the
- 486 Catastrophic 2020 Yangtze River Basin Flooding in Southern China. The Innovation. 1(2),
- 487 100038.

- Weill, S., Mouche, E., Patin, J., 2009. A generalized Richards equation for surface/subsurface flow
  modelling. Journal of Hydrology. 366(1-4), 9-20.
- 490 Woo, S.I., Rodrigo, S., 2018. Simulation of penetration of a foundation element in Tresca soil using
- 491 the generalized interpolation material point method (GIMP). Computers and Geotechnics. 94,
- 492 106-117.
- 493 Ying, C., Zhang, K., Wang, Z.N., Siddiqua, S., Makeen, G.M.H., and Wang, L., 2021. Analysis of the
- 494 run-out processes of the Xinlu Village landslide using the generalized interpolation material
- 495 point method. Landslides. 18, 1519-1529.
- 496 Zhu, Y., Ishikawa, T., Subramanian, S.S., Luo, B., 2020. Simultaneous analysis of slope instabilities
- 497 on a small catchment-scale using coupled surface and subsurface flows. Engineering Geology.
  498 275, 105750.