

Viscoplastic Modelling of Rainfall-driven Slow-moving Landslides: Application to California Coast Ranges

Xiang Li¹, Alexander L. Handwerger^{2,3}, and Giuseppe Buscarnera¹

¹ Department of Civil and Environmental Engineering, Northwestern University, Evanston, USA

²Jet Propulsion Laboratory, California Institute of Technology, Pasadena, USA.

³Joint Institute for Regional Earth System Science and Engineering, University of California, Los Angeles, USA.

ABSTRACT

Slow-moving landslides are widely observed in mountainous areas worldwide. While most of these landslides move slowly downslope over long periods of time, some ultimately accelerate rapidly and fail catastrophically. Simulating the landslide creep movement triggered by environmental factors such as precipitation, is therefore necessary to anticipate potential damaging effects on proximal infrastructure, habitat, and life. Here, we present a physically-based model that links pore-water pressure changes in the landslide mass with a new viscoplastic constitutive law designed to capture different temporal trends in slow-moving landslides. The model accounts for landslide velocity changes caused by rainfall infiltration through the Terzaghi's effective stress principle, thus directly resolving the deformation of the active shear zone. Calibration and validation of the computations benefited from both ground-based and remote sensing data for three active landslides in the California Coast Ranges, USA. We find that our model can accurately describe both slow quasi-continuous and episodic movement commonly displayed by active landslides. Although inherent limitations of the viscoplasticity framework did not enable us to describe catastrophic landslide acceleration, our model provides versatile tools that can be used to analyze and describe distinct types of slow-moving landslide dynamics.

27

28 **Keywords:** slow-moving landslides, rainfall infiltration, constitutive modeling, rate-dependent strength.

29 **1 Introduction**

30 Slow-moving landslides (Hung et al., 2014) are widely observed in mountainous areas (Keefer
31 and Johnson, 1983; Baum and Reid, 1995; Oberender and Puzrin, 2016; Lacroix, et al., 2020).
32 These landslides can remain active for decades or centuries (Mackey et al., 2009) and often exhibit
33 velocity variations related to local environmental changes (Corominas et al., 2005; Bennett et al.,
34 2016; Hillel et al., 2004; Cascini et al., 2010). With velocities around 1m/year, slow-moving
35 landslides can cause severe damage to proximal infrastructure and habitats (Mansour et al., 2011).
36 Some of them can even transition from slow (within 1 m/year) to rapid (more than 1 m/s)
37 displacement and lead to significant damage and even fatalities (Hendron and Patton, 1985; Li et
38 al., 2020). It is therefore of great importance to interpret the velocity change of slow-moving
39 landslides in order to manage the potential damage.

40 Slow-moving landslides are commonly driven by pore-water pressure transients that can result
41 from infiltrating precipitation. When infiltration occurs, the pore-water pressures rise and cause a
42 decrease in the normal stress applied on the landslide material (Terzaghi, 1925). Consequently, the
43 resistance to downslope sliding is diminished and this can trigger the activation or acceleration of
44 the landslide. Thus, hydrologic models have been developed to compute precipitation-induced
45 pore-water pressures within the landslide body and can be used to explain observed landslide
46 velocity variations (Iverson, 2000; Van Asch et al., 1996; Baum, 2000; Cohen-Waeber et al.,
47 2018). Unsaturated effects from the local vadose zone (Finnegan et al., 2021) and flow induced
48 particle redistribution (Wang and Sassa, 2003; Cui et al., 2019) have also been shown to play an
49 important role in controlling the onset of landslide motion. In addition, the flow-deformation
50 coupling effects on landslides dynamics have been taken into account (Iverson, 2005), showing

51 that the shear zone volumetric deformation (in dilation or contraction) determines whether a
52 landslide will exhibit steady movement or runaway acceleration.

53 In addition to hydrological effects, the material mechanical properties will also influence the
54 landslide behaviors. Earthen materials normally exhibit time-dependent behaviors such as creep,
55 relaxation, and rate-sensitivity (Augustesen et al., 2004; Tika et al., 1996; Scaringi et al., 2018).
56 Such properties often influence the mobility of landslides and can be computed through rate-
57 dependent strength models based on viscoplasticity (Mitchell et al., 1968; Liingaard et al., 2004;
58 Marinelli et al., 2018). It is found that the strength of earthen materials can evolve if the shear rates
59 vary from low (within 1 m/year) to high (more than 1m/s) (Alonso et al., 2016; Scaringi et al.,
60 2018). Under low shear rates, earthen materials normally exhibit rate-strengthening (Rice et al.,
61 2001; Wedage et al., 1998); while high shear rates can induce rate-weakening (Di Toro et al., 2006;
62 Mizoguchi et al., 2007). A recent study of the Two Towers landslide, northern California (study
63 area of this paper) indicated that the shearing resistance is invariant under the range of sliding rates
64 exhibited in the field (Schulz et al, 2018). Yet, the ring shear tests used to characterize the Two
65 Towers landslide material showed the friction angle varies between $\sim 21^\circ$ and $\sim 24^\circ$ with shear rates
66 from 0.01 to 1 mm/s (both rate weakening and rate strengthening were observed in this range).
67 Such changes, although small, indicate some degree of rate-dependent behavior, which can be
68 characterized with viscoplasticity (e.g., Mitchell et al., 1968).

69 Viscoplasticity has been used widely to quantify the creeping movement of landslides in response
70 to precipitation (Angeli et al., 1996; Van Asch et al, 2007; Oberender and Puzrin, 2016; Conte et
71 al., 2014). Viscoplastic models are able to describe a variety of slow-moving landslide behaviors
72 and have additional modeling benefits because they ensure stable computations of landslide
73 creeping under quasi-static conditions (i.e., no runaway instability of the landslide mass) (Perzyna,

74 1963; Needleman, 1988). Despite earthen material viscosity can be limited, which may prevent
75 them from accurately describing some of the mechanisms that govern the landslide behavior
76 (Schulz et al, 2018; Iverson, 2020), they can be used to quantify the landslide creep movement
77 accurately.

78 In this manuscript, we develop a hybrid rate-strengthening rheological law able to account for pre-
79 yield plastic deformation, which we argue is a key component of landslide deformation commonly
80 missing in landslide models (di Prisco and Imposimato, 1997; Zambelli et al., 2004; Shi et al.,
81 2018), that can describe the continuous and episodic movements exhibited by slow-moving
82 landslides. This rheological model is used in conjunction with the 1D infinite slope model
83 (Skempton and Lory, 1957) and a hydrologic framework to simulate rainfall infiltration (Lizarraga
84 and Buscarnera, 2018). The paper is outlined as follows: first, we describe the features of the
85 numerical model. Then, we test our formulation by simulating simple monotonic and cyclic pore
86 water pressure variations that enable us to better constrain the impact of each model parameter.
87 Finally, our model is applied to capture the movement of three active landslides in the California
88 Coast Ranges, USA.

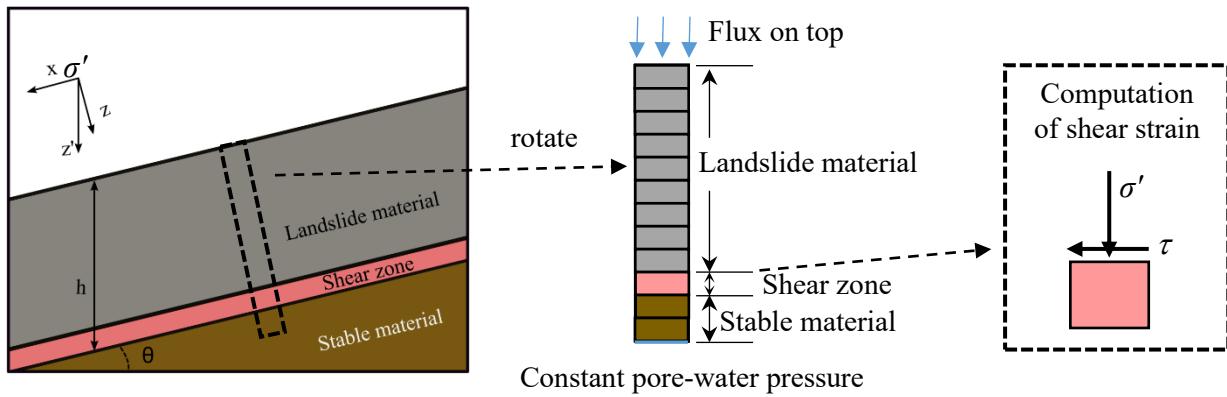
89 **2 Model description**

90 *2.1 Landslide and hydrologic model*

91 Our landslide model is constructed in accordance with a 1D infinite slope geometry and has three
92 components (Fig. 1): (1) a thick, rigid landslide body, (2) a thin deforming shear zone, and (3)
93 undeforming stable material (e.g., bedrock) below the moving mass. This landslide model
94 geometry is based on evidence from numerous field studies that have shown that the thickness of
95 slow-moving landslides is a few meters to tens of meters, while the thickness of the shear zone

96 varies from few centimeters to several tens of centimeters (Corominas et al., 2000; Leroueil, 2001;
 97 Puzrin and Schmid, 2011; Schulz et al., 2018).

98 We simulate pore-water pressure (p_w) changes inside a saturated landslide using a hydrologic
 99 model that is designed to solve a mass balance equation (Eq. 1) (Richards, 1931). Here we ignore
 100 the nonlinear effects that stem from unsaturated conditions (Yeh and Ward, 1980), which implies
 101 that the nonlinear functions that describe soil-water interactions in the vadose zone (i.e., Water
 102 Retention Curve and Hydraulic Conductivity Function) are encapsulated into two constants,
 103 namely the storage coefficient, S_s , and the saturated permeability, k_s . This simplification leads to
 104 a linear diffusion equation that has been widely used for simple pore-water pressure simulations
 105 in landslide studies (e.g., Iverson 2000; Cohen-Waeber et al., 2018; Berti and Simoni 2010). The
 106 change in pore-water pressure can be computed through



107
 108 **Figure 1.** Schematic of the infinite slope model, along with the corresponding boundary conditions and shear
 109 strain computation at the reference shear zone element used for the simulations. The schematic is not to scale.
 110 The thickness of the landslide material, depth of the shear zone, and slope inclination θ of each case study are
 111 described later in Section 5.

112
$$S_s \frac{\partial h_w}{\partial t} = \frac{\partial}{\partial z} (k_s \frac{\partial (h_w + z)}{\partial z}), \quad (1)$$

113 where z is the normal distance from the ground surface, h_w is water pressure head (pore-water
 114 pressure p_w divided by the unit weight of water). This partial differential equation is solved

115 through the algorithm proposed by Lizárraga and Buscarnera (2018), which enables a
116 straightforward incorporation of permeability contrasts. The latter feature is useful to account for
117 permeability changes between the landslide body, shear zone, and stable ground (Baum and Reid,
118 1995).

119 Nereson et al. (2018) examined the differences in permeability within the Oak Ridge landslide,
120 central California. Their results indicated that the shear zone permeability is around two orders of
121 magnitude lower than the overlying landslide material, while the stable material below the
122 landslide shear zone has a permeability around two times higher than the landslide material. All
123 case studies in this manuscript are located in the same geological unit (Franciscan Complex
124 mélange) as the Oak Ridge landslide. Thus, we adopt this stratigraphic framework for our model
125 simulations. We set the saturated permeability of the three components (Fig. 1) in our model (the
126 ratios between shear zone k_s , sliding material k_s , and stable material k_s are 1:0.01:0.005). The top
127 boundary condition is an imposed water flux from rainfall data. We also set a constant pore-water
128 pressure boundary condition three meters below the sliding surface allocated in the stable material,
129 which is consistent with prior observations by Iverson and Major (1987) and serves as the bottom
130 boundary in our analysis.

131 The hydrologic model is then linked to our mechanical model through the effective normal stress
132 theory. The simulated rainfall-induced changes in pore-water pressure cause changes in the
133 effective normal stress, defined as $\sigma' = \sigma - p_w$, where σ is the total normal stress at the considered
134 depth. The strain resulting from such changes in effective stress is computed through the
135 constitutive models outlined in section 2.2.

136 2.2 *Constitutive models*

137 Here we outline a viscoplastic flow model to describe slow-moving landslides. In our model, the
 138 inelastic deformation captures both shear strain (in the sliding direction) and normal strain (in the
 139 direction perpendicular to the slope). We apply the Mohr-Coulomb yield criterion (Coulomb,
 140 1776):

$$141 \quad f = \tau - \eta_y \sigma', \quad (2)$$

142 where f is the yield function, τ is the shear stress, and η_y is the stress ratio at yield. $\eta_y = \tan \varphi$,
 143 φ is material friction angle at yield. Although inelastic strains due to suction loss may play a key
 144 role in shallow landslide deformation processes (Li et al., 2021; Chen and Buscarnera, 2021), thus
 145 requiring specific constitutive laws (e.g., Alonso et al., 1990), unsaturated effects have not been
 146 taken into account in this study, in that for most landslides in the selected studied area the shear
 147 zones are below the phreatic level and, thus, fully saturated. In addition, the plastic shear strain γ^p
 148 is determined by the viscoplastic flow rule (Perzyna, 1963;1966):

$$149 \quad \frac{d\gamma^p}{dt} = \phi(f) \frac{\partial g}{\partial \tau}, \quad (3)$$

150 where $\phi(f)$ is the viscous nucleus that controls the magnitude of the plastic strain rate. Possible
 151 expressions for these functions will be specified in the section 2.3. The direction of the viscoplastic
 152 strain rate is defined by the stress gradient of the plastic potential g (equals to f for an associated
 153 flow rule). Although the earthen material viscosity can be relatively small, and other mechanisms
 154 such as dilation or compaction-induced pore-water pressure changes may be important in
 155 controlling landslides (e.g., Iverson, 2005), this class of rheological models provide a platform that

156 is versatile for landslide simulations aimed at quantifying slope creep movements (Van Asch,
157 2007; Angeli et al., 1996; Oberender and Puzrin, 2016; Conte et al., 2014).

158 2.3 *Rheological law*

159 The viscous nucleus (Eq. 3), which quantifies the strain rate, is a core element of a viscoplastic
160 rheology. Here, viscoplasticity is implemented by following the overstress approach proposed by
161 Perzyna (1966). Such framework can be regarded as a generalization of the Bingham rheology
162 (Bingham, 1917) for general stress states and yielding criteria. As such, this framework has been
163 widely adopted to interpret the results of earthen material laboratory tests (Liingaard et al., 2004)
164 and simulate landslide movement (Angeli et al., 1996; Oberender and Puzrin, 2016; Van Asch et
165 al., 2007). Standard expressions of the viscous nucleus rely on power law functions (Van Asch et
166 al, 2007; Marinelli et al., 2018), as follows

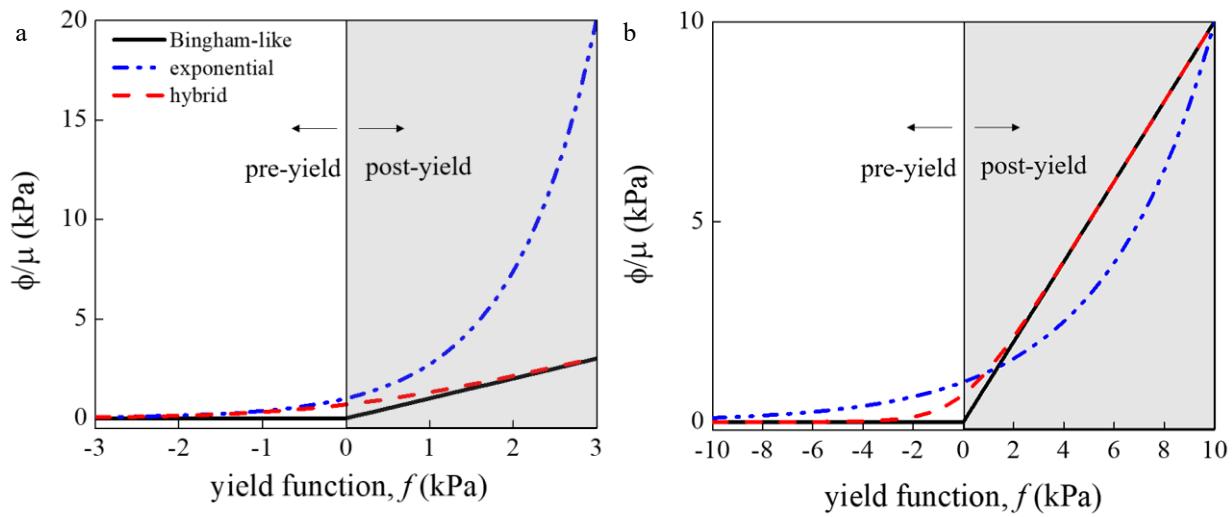
$$167 \phi(f) = \begin{cases} \mu f^\alpha, & f \geq 0 \\ 0, & f < 0 \end{cases}, \quad (4)$$

168 where μ and α are model parameters. The expression above converges to a Bingham-like rheology
169 when $\alpha = 1$. In addition, by setting $\phi(f) = 0$ for $f < 0$ no viscoplastic strain rate can emerge
170 prior to yielding, thus indicating a bilinear trend characterized by permanent deformations only if
171 the yield criterion is surpassed ($f > 0$). However, evidence from laboratory tests suggests that
172 this approach can be excessively restrictive for earthen materials, which exhibit time-dependency
173 much earlier than shear failure, including in the presence of overconsolidated states (Augustesen
174 et al., 2004; Shi et al., 2018). To better account for these effects, exponential forms have been
175 proposed (di Prisco and Imposimato, 1996) for sand:

$$176 \phi(f) = \mu e^{\alpha f}. \quad (5)$$

177 Although Eq. 5 allows non-zero pre-yielding viscosity, by letting the viscoplastic deformation
 178 gradually augment as the stress state moves away from the failure envelope, its exponential form
 179 tends to produce excessive plastic strain rate once the yield surface is surpassed. We provide an
 180 illustrative example of this in Fig. 2a for a viscous nucleus characterized by $\alpha=1$. Our example
 181 shows that even a small excess of the yield threshold (only 3 kPa in our example corresponding to
 182 a water level increase of 0.3 m), the exponential law predicts a shear strain rate that is more than
 183 double the rate predicted by the Bingham-like model. To address this issue, we propose a hybrid
 184 law as a mathematical compromise able to blend the benefits of above two forms above, as follows:

185 $\phi(f) = \mu \ln(1 + e^{\alpha f})$. (6)



186

187 **Figure 2. Factorized viscous shear strain rate (by $1/\mu$, parameter that scales the magnitude) versus yield**
 188 **function value for different expressions of viscous nucleus. a) Dashed-dotted blue, dashed red, and black lines**
 189 **show model predictions for the exponential, hybrid, and Bingham-like models with $\alpha = 1$. b) Blue, dashed red,**
 190 **and black lines show model predictions with $\alpha = 1$ for the hybrid and Bingham-like and $\alpha = 0.23$ for the**
 191 **exponential law. These simulations show that changing the power-law rheology term can lead to the same strain**
 192 **rate at the maximum yield function.**

193 Such a model can capture both pre-yield viscoplastic strain and post-yield strain rates comparable
 194 to those of widely used Bingham-like models. This effect could not have been achieved by
 195 modulating the parameters of the exponential rheology in Eq. 5 alone, because setting an ideal

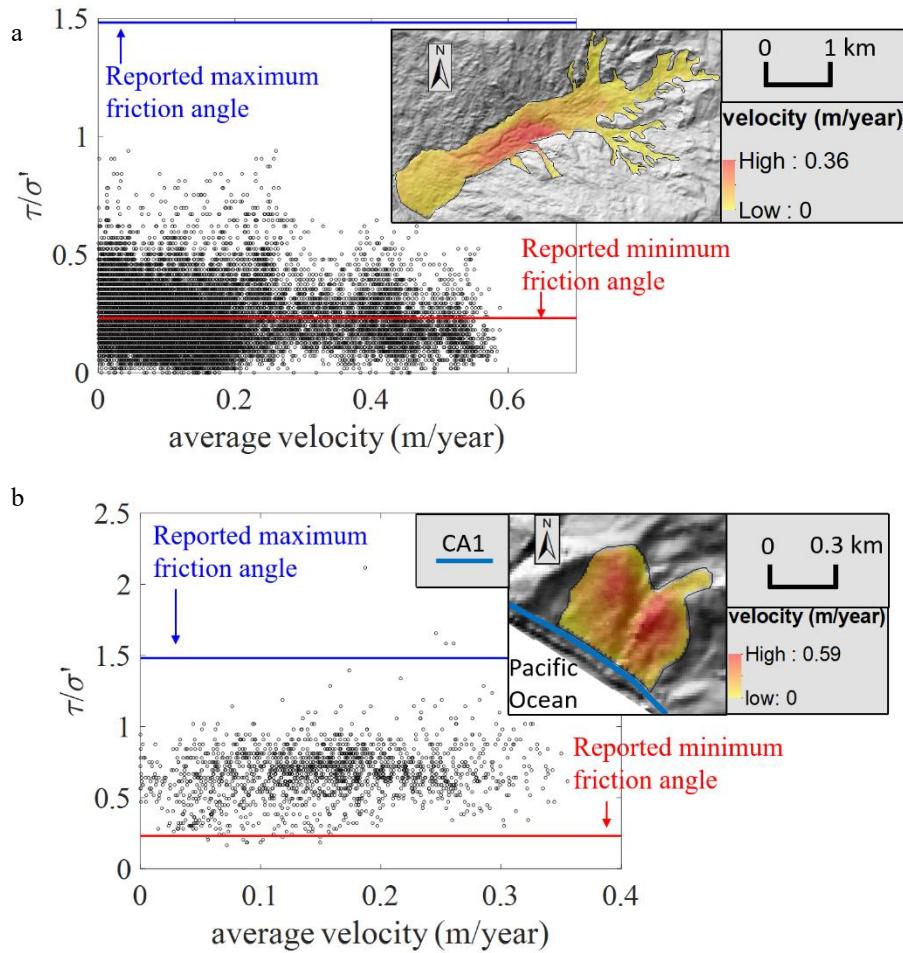
196 strain rate at large overstress values ($f=10$ kPa in Fig. 2b) leads to overestimation of the strain
197 rates in the pre-yielding regime (strain developed when f is 10 kPa). By contrast, the hybrid law
198 we proposed enables a Bingham-like rheology to be recovered at large overstress values, while
199 capturing slow growth (but non-zero) viscoplastic strain rates in the pre-yield regime. Thus, it can
200 be regarded as a more versatile platform to describe the rheology of earthen materials.

201 *2.4 Indication of pre-yield viscosity*

202 As mentioned above, laboratory measurements have shown that earthen materials exhibit viscous
203 properties even within the elastic domain (di Prisco and Imposimato, 1996; Sekiguchi, 1984). To
204 test whether landslides exhibit pre-yield viscosity at the field scale, we examine relationships
205 between measured landslide velocity and slope angle for the Boulder Creek and Mud Creek
206 landslides in California (a detailed description of these landslides is provided in Section 4.1). The
207 goal of this analysis is to link the landslide mobility to the stress state acting on the material, aiming
208 at investigating if viscous effects may emerge before the material is driven into the plastic domain.

209 The Boulder Creek landslide has a mean ground surface slope angle of 15° and has been exhibiting
210 quasi-steady motion (the monitored displacement over time shows nearly constant increment) for
211 decades or longer (Handwerger et al., 2013; 2019; Mackey and Roering, 2011). The Mud Creek
212 landslide is notably steeper with a mean ground surface slope angle of 32° and exhibited episodic
213 motion for a minimum of 8 years before it collapsed catastrophically. We measure the average
214 landslide velocity from a previously published surface velocity dataset (Handwerger et al., 2019).
215 The landslide surface velocity was quantified using satellite-based interferometric synthetic-
216 aperture radar (InSAR) data, a remote sensing technique that can measure mm- to cm-scale ground
217 surface motion (see Section 5 for more details). We then calculate the stress ratio (shear
218 stress/effective normal stress in nearly dry condition) using a digital elevation model (DEM,

219 resolution 12 m) provided by the German Space Agency (DLR). The slope angle determines the
 220 magnitude of the gravitational loading components along both normal and tangential directions (z
 221 and x displayed in Fig. 1), which effects the ratio between shear and normal stress (stress ratio).
 222 For simplicity, we assume the landslide thickness is constant and is 20 m for Mud Creek and 40 m



223

224 **Figure 3. Pre- and post-yield motion analyses of the Boulder Creek and Mud Creek landslide. The ratio of**
 225 **shear stress divided by the effective normal stress vs. average velocity for a). Boulder Creek landslide, b).**
 226 **Mud Creek landslide. Inset images are the average downslope InSAR velocity map of each landslide plotted on top**
 227 **of its hillshade individually. Light blue line at base of Mud Creek shows California State Highway 1 (CA1). The**
 228 **data are binned by pixels with the same slope angle. Horizontal red line shows the stress ratio corresponding**
 229 **to 13° friction angle, which is the minimum friction angle reported by Keefer and Johnson, 1978; blue line**
 230 **shows the stress ratio of 56° friction angle, which is the maximum value reported by Roadifer, et al., 2009.**
 231 **InSAR data are from Handwerger et al. (2019) and DEM is from TanDEM-X. TanDEM-X data used is under**
 232 **copyright by the DLR.**

233 for Boulder Creek (details explained in the Section 5). From classical slope stability analysis
234 (Duncan, 1996), the relation between the stress ratio and the value at yield can indicate if the slope
235 is predicted to be stable or unstable (the smaller the stress ratio, the further it departs from the
236 material yield status).

237 Fig. 3a shows a comparison between the stress ratio and velocity for the Boulder Creek landslide.
238 We find that for even low stress ratios, there are abundant landslide pixels that display non-
239 negligible movement. Similarly, we compare the relation between average InSAR surface velocity
240 and stress ratio for the Mud Creek landslide (Fig. 3b). Due to the significantly steeper slope angle,
241 Mud Creek has a much higher stress ratio overall, but also showed some movement at low stress
242 ratios. Geotechnical investigations (Keefer and Johnson, 1983; Schulz et al., 2018; Nereson et al.,
243 2018) recorded that for landslide materials hosted in the Franciscan Mélange, the rock type
244 common to both landslides, the minimum friction angle is around 13° (Keefer and Johnson, 1983)
245 and the maximum friction angle is around 56° (Roadifer et al., 2009). Both stress ratios are
246 depicted in Fig. 3. Our findings indicate creeping deformation occurs at stress ratios below the
247 frictional limit and suggests the landslides exhibit a viscous material rheology in the pre-yield
248 regime.

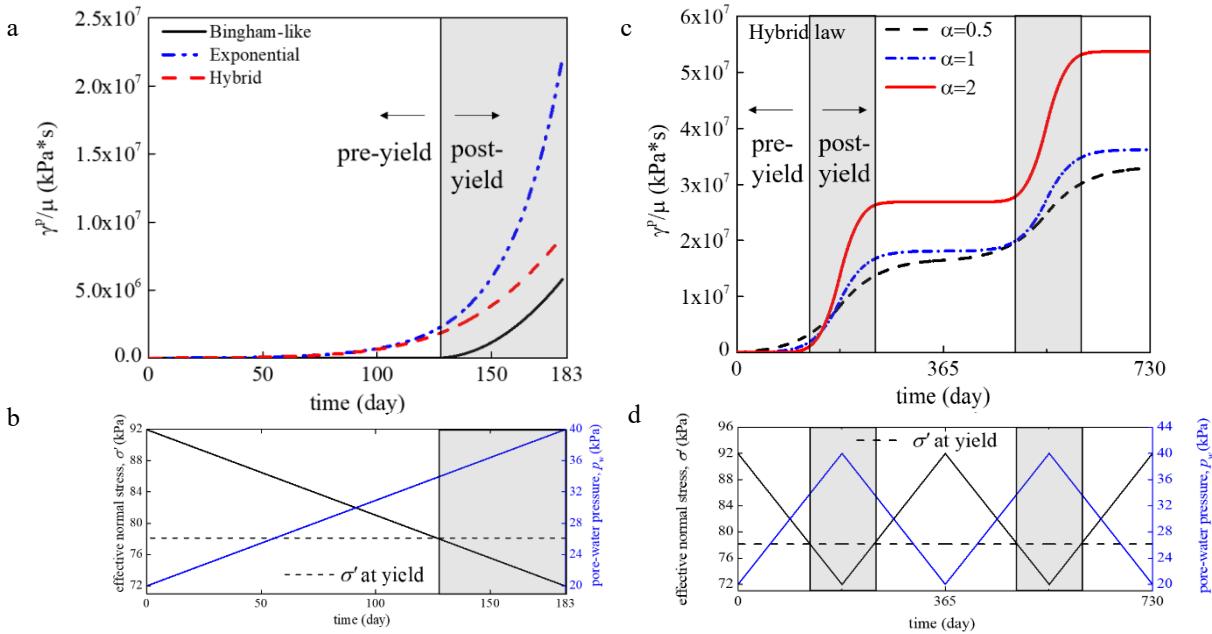
249 **3 Model testing**

250 *3.1 Monotonic increase of pore-water pressure*

251 In the previous section, factorized viscoplastic strain rates corresponding to different viscous
252 nucleus expressions were compared. Here, to further illustrate each model's performance in
253 response to more realistic pore-water pressure variations in landslides, all rheological laws are
254 tested with a simulated p_w increase of 20 kPa over 180 days (i.e., a 2 m water level rise which
255 approximates the water level change experienced by the active landslides in the California Coast

256 Range (Iverson and Major, 1987; Schulz et al., 2018; Finnegan et al., 2021)) directly applied to
 257 the landslide sliding surface (Fig. 4b, other parameters are listed in the figure caption). The same
 258 value of viscous parameter $\alpha = 1$ is used for all the simulations. Since the parameter μ controls
 259 the magnitude of the plastic shear strain (γ^p), here the factorized viscoplastic shear strain (γ^p/μ)
 260 is used as a basis for the model comparisons (Fig. 4a).

261 *3.2 Sensitivity tests for hybrid model mechanical parameters*



262

263 **Figure 4. Comparisons of the three viscoplastic models. Shear strain is computed from rheological laws in**
 264 **response of monotonic increased and cyclic pore-water pressure. a) Factorized viscoplastic shear strain**
 265 **calculated by each rheological law. b) Pore-water pressure monotonic variation and corresponding effective**
 266 **normal stress. c) Factorized viscoplastic shear strain calculated Hybrid law with different value of α . d) Cyclic**
 267 **pore water pressure variation, corresponding effective normal stress change. For this synthetic landslide**
 268 **experiments the model parameters were chosen to resemble those reported for typical landslide settings in the**
 269 **California Coast Ranges (Schultz et al., 2018), $h = 6$ m, $\theta = 15^\circ$, $\gamma_{sat} = 22$ kN/m³, $\phi = 21^\circ$.**

270 Fig. 4b shows the effective normal stress variation caused by this synthetic hydraulic event. The
 271 yield surface is approached after about 130 days. Our model results show that the normalized shear
 272 strain computed from the Bingham-like model begins to increase after 130 days, while the

273 exponential law predicts an earlier initiation of the movement after 60 days and a predicted
274 movement three times larger than those obtained with the Bingham law (Fig. 4a).

275 Our new hybrid law predicts that shear strain initiates after about 80 days, which is 50 days before
276 the yield surface is approached, while providing total displacement at the end of the pore-water
277 pressure growth period that is similar to those obtained from the Bingham-like model (Fig. 4a).
278 This result confirms the ability of the proposed hybrid rheology to provide a compromise between
279 Bingham-like models widely tested for the active stage of landslide motion and exponential
280 formulations tailored for describing pre-yielding sliding behavior. Hereafter, parametric analyses
281 are conducted to explore the effect of the model parameters.

282 The parameters of the proposed hybrid mechanical model are φ , μ and α . Among them, φ
283 determines the pore-water pressure limit enabling episodic slips (i.e., the landslide mobilization
284 time), while μ governs the magnitude of the displacement. α influences the sensitivity of the
285 sliding behavior against pore-water pressure variance; as an outcome, it affects the temporal
286 history of the sliding response in both magnitude and rate (Fig. 4c).

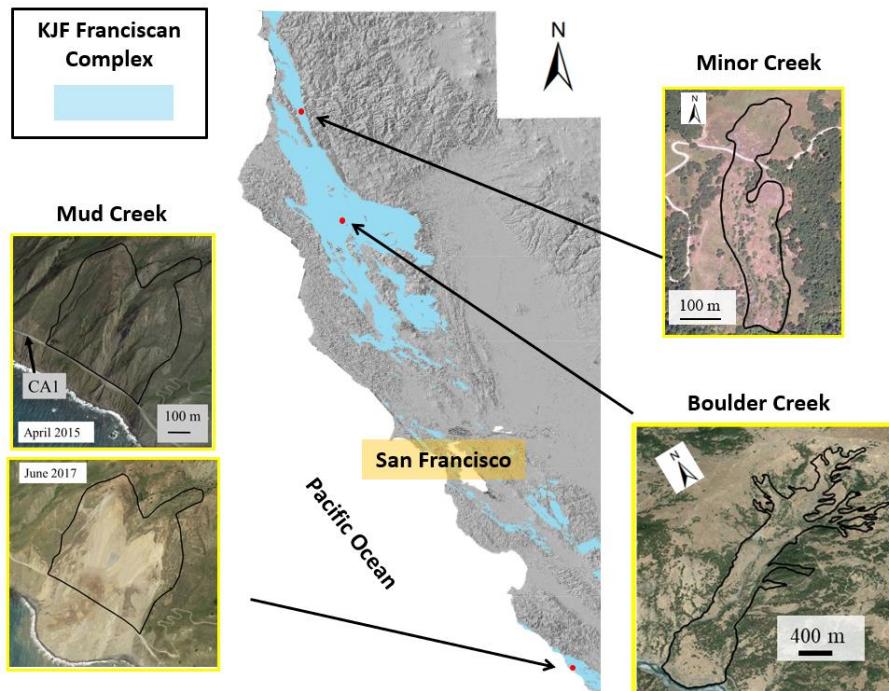
287 Fig. 4d shows another simulated pore-water pressure change and the predicted landslide response.
288 Here we apply cyclic triangular waves of pore-water pressure of 20 kPa amplitude to approximate
289 cyclic seasonal rainfall effects. We find that when $\alpha = 0.5$ (at 130 days), the sliding behavior prior
290 to the stress path approaching the yield surface (50 days in advance) is discernible, while the
291 displacement at the peak of pore-water pressure (around 180 days) is relatively small compared to
292 the other simulations. By contrast, when $\alpha = 2$, pre-yielding effects are suppressed, and the
293 response involves sharp episodic slips occurring only upon violation of the yield criterion. Thus,
294 a higher α leads to marked velocity changes between periods with higher and lower pore-water
295 pressure, which represent the wet and dry seasons commonly experienced by real landslides (e.g.,

296 Corominas et al., 2000). In other words, the history of the rates of landslide movement is governed
297 by α . In the next section we will calibrate these model parameters to data from three landslides in
298 California.

299 **4 Case Studies**

300 *4.1 Sites of interest*

301 Thousands of slow-moving landslides have been identified in the California Coast Ranges
302 (Bennett et al., 2016; Handwerger et al., 2019b; Keefer and Johnson, 1983; Kelsey et al., 1995;
303 Mackey and Roering, 2011; Scheingross et al., 2013). These landslides are widespread in this



304

305 **Figure 5. Landslide test sites. Northern and Central California Coast Ranges, showing the Franciscan Complex**
306 **mélange unit draped over a hillshade of the topography. The hillshade was generated from a 12-m TanDEM-**
307 **X DEM. The three landslide test sites used in this paper are marked on the map, along with inserts showing**
308 **oblique Google Earth images. For Mud Creek landslide, both the images before and after catastrophic failure**
309 **are shown.**

310 region due to active tectonics, mechanically weak rocks, and high seasonal precipitation
311 (Scheingross et al., 2013; Roering et al., 2015). The rainfall in California is seasonal with the vast

312 majority of precipitation occurring between October to May (Swain, 2021). Most of the landslides
313 located within the Jurassic-Cretaceous Franciscan Mélange (KJf) (Roering et al., 2015), which is
314 a clay-rich complex with various more resistant rocks such as sandstone, shales, serpentinite, and
315 conglomerates (Bailey et al., 1964; Rutte et al., 2020).

316 Here, Minor Creek landslide, Boulder Creek landslide, and Mud Creek landslide have been
317 selected as cases of study to test our model performance. We summarize our approach to calibrate
318 our model in Table 1. Minor Creek was monitored between 1982-1985 using ground-based tools

319 **Table 1.** parameters calibration guidance

Model parameter	Description	Calibration from	Calibration guidance
k_s (m/s)	Saturated permeability	Pore-water pressure	Increase the value if the simulated pore pressure lags behind the measured data
S_s (m ⁻¹)	Storage coefficient	Pore-water pressure	Increase if the simulated pore pressure amplitude is smaller than the measured data
φ (°)	Friction angle	Movement	Decrease if the simulated sliding initiates later than observation or no sliding can be computed
α (-)	Pre- and post-yield viscosity ratio	Movement	Decrease if the movement difference in dry and wet season is larger than the measured data
μ (kPa*s) ⁻¹	Magnitude of viscosity	Movement	Increase if the simulated sliding magnitude is smaller than the measured data

320
321 including piezometers for measuring pore-water pressure, and extensometers for monitoring
322 displacement (see details in Iverson and Major, 1987). Mud Creek landslide and Boulder Creek
323 landslide have no ground-based data available and instead their displacement was measured
324 between 2015 and 2017 through satellite-based InSAR techniques (see details in Handwerger et
325 al., 2019). Minor Creek and Boulder Creek landslides have been exhibiting slow and episodic
326 sliding for decades or longer. Mud Creek landslide is also known to have displayed slow sliding

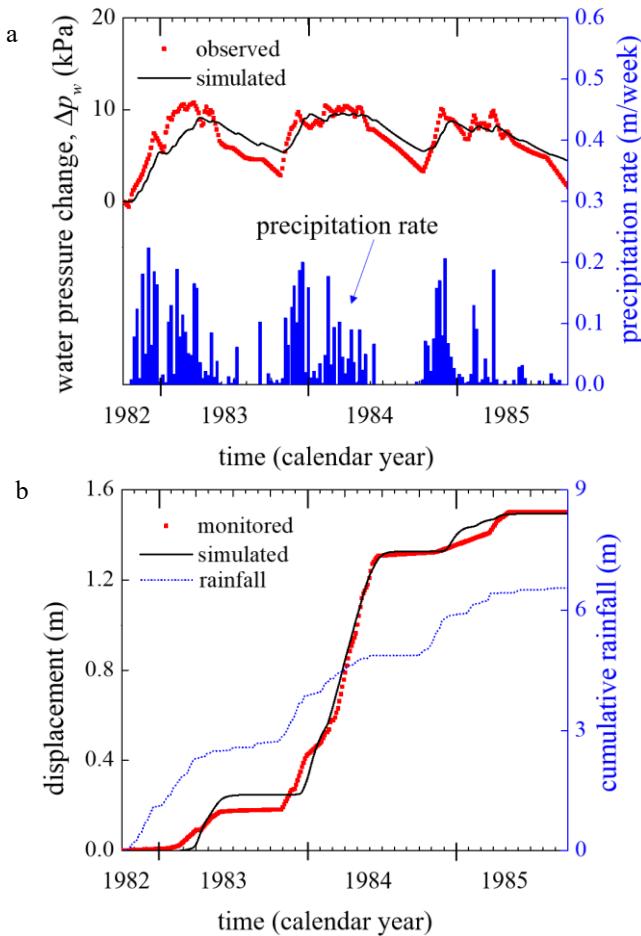
327 for more than 8 years, but this changed when it failed catastrophically on a dry day (May 20, 2017)
328 following a prolonged period of heavy rainfall. This sudden acceleration heavily damaged the
329 California State Highway 1 (CA1) (Fig. 5), resulting in road closure between May 2017 and July
330 2018 and an estimated cost of \$54 million in repairs (Caltrans report, 2018). These landslides
331 exhibit substantially different trends of movement over time; thus, they are good candidates to test
332 the model versatility. Details of each case and correspondent model performance are discussed in
333 the following sub-sections.

334 *4.2 Minor Creek landslide*

335 Minor Creek landslide (Fig. 5), a compound, complex, slow-moving landslide, covers about 10
336 hectares in Redwood Creek drainage basin, northern California Coast Ranges. Iverson and Major
337 (1987) acquired three years of detailed rainfall, groundwater and movement data (Fig. 6a and 6b)
338 of this landslide from October 1982 to September 1985. We digitized the measured rainfall and
339 pore-water pressure based on the results shown in Fig. 10 of Iverson (2005). The average slope
340 angle is 15° ; the thickness of the landslide along its longitudinal axis is 6 m; thickness of the shear
341 zone is around 1 m (Iverson, 1985).

342 The precipitation was monitored with a rain gage located at the site of the landslide, which is set
343 as the top boundary condition of the hydraulic simulation in order to compute the rainfall induced
344 pore-water pressure. The initial water pressure is set based on the shear zone pore-water pressure
345 (Fig. 6a) assuming hydro-static conditions. The lower boundary condition is set as a constant pore-
346 water pressure value three meters below the sliding surface as discussed above to reflect the
347 observed hydrological condition that deep pore-water pressure barely changed. We calibrated our
348 model parameters for the shear zone material using trial and error following the calibration

349 processes illustrated in Table 1. We found that our simulated pore-water pressure variation is
 350 consistent with the monitoring data (Fig. 6a) with the hydraulic parameters in Table 2.



351

352 **Figure 6. Pore-water pressure, rainfall, and displacement of Minor Creek landslide during 1982 ~1985. a)**
 353 **Monitored and simulated pore-water pressure variation at the sliding surface and the precipitation rate; b)**
 354 **monitored and simulated landslide movement and cumulative rainfall, model parameters shown in Table 2.**
 355 **Monitored data are digitized from Iverson and Major (1987).**

356 The episodic slip movements of this landslide site (Fig. 6b) are driven by pore-water pressure
 357 changes during the wet and dry seasons. The pore-water pressure rises rapidly after onset of the
 358 wet season, remains relatively high during the wet season, and decreases slowly throughout the
 359 dry season. As a result, the landslide is barely active during the dry season and moves primarily
 360 during the wet season (Fig 6b). Such step-like episodic displacements suggest a high value of
 361 parameter α . Our best-fit model parameters are $\alpha=8$, $\mu=2.1\times 10^{-8}$ (kPa*s) $^{-1}$, and friction angle (φ)

362 around 19° (Table 2). Fig. 6b illustrates that the landslide movement of Minor Creek landslide can
363 be simulated accurately by our new proposed hybrid rheological model.

364 **Table 2.** model parameters for the selected case studies

Model parameters	Minor Creek	Boulder Creek	Mud Creek
k_s (m/s)	4.45E-6	4.6E-6	4.6E-6
S_s (m ⁻¹)	0.27	0.03	0.07
α (-)	8.00	0.15	0.70
μ (kPa*s) ⁻¹	2.1E-8	2.1E-8	2.1E-8
φ (°)	18.9	26.1	48.5

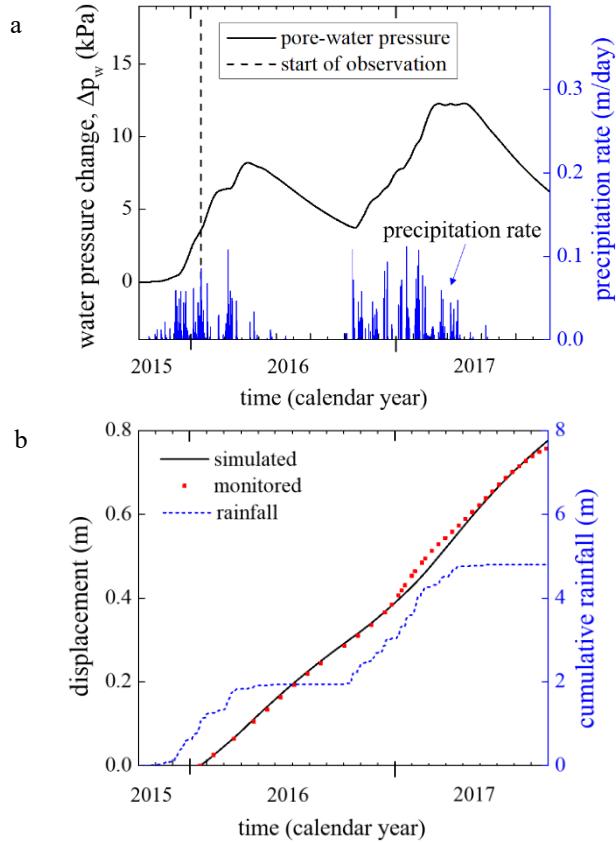
365
366 Importantly, the model captures the relatively large displacement displayed by Minor Creek from
367 the end of 1983 to the beginning of 1984 and the smaller displacements in the other wet seasons.
368 This large displacement was caused by a pore-water pressure change that approaches its highest
369 value (~10 kPa) for more than half of the year (Fig. 6a). The longer period with higher pore-water
370 pressure leads to the apparent active landslide movement (around 1 m/year, still categorized as a
371 slow landslide by Hungr (2014)). The results show some mismatches between our pore-water
372 pressure and displacement simulations and the monitoring data, such as, predicting lower pore-
373 water pressures during the wet season of water year 1983; simulating higher pore-water pressures
374 at each dry season compared with the monitoring data; obtaining delayed, higher magnitude
375 movement in the first year. Despite these differences, the overall agreement between our computed
376 results and the field data corroborates the model's ability to describe both hydraulic and
377 mechanical behavior in monitored landslides.

378 4.3 *Boulder Creek landslide*

379 Boulder Creek landslide (Fig. 5), northern California Coast Ranges, has displayed stable sliding
380 for decades (Mackey and Roering, 2011). Although no ground-based monitoring of deformation
381 or pore-water pressure is available at the site, surface movements from January 2016 to October
382 2017 (Fig. 7b) were measured by Handwerger et al. (2019) via InSAR images acquired by the
383 Copernicus Sentinel-1 A/B satellites. The InSAR data show that the landslide exhibits a nearly
384 constant displacement rate (quasi-continuous slow creeping with minor seasonal variations), thus
385 with a temporal trend departing considerably from the episodic motion discussed previously. The
386 average inclination of this landslide is around 15°, the area is around 310 hectares (Handwerger et
387 al., 2013), and the estimated thickness is 40 m (Mackey and Roering, 2011). We simulated the
388 pore-water pressure time history at the landslide base by assuming a nearly saturated initial
389 condition. We assume saturated conditions in that field data from other landslide sites in the KJF
390 show that the groundwater table remains within 2-3 m of the ground surface during the dry season
391 and rises to the ground surface during the wet season (Iverson and Major, 1987; Schulz et al.,
392 2018; Hahm et al., 2019; Finnegan et al., 2021). We used precipitation data (Fig. 7) acquired by
393 National Oceanic and Atmospheric Administration (NOAA) as the surface boundary condition
394 (around 50 km from the landslide). The hydrological parameters (Table 2) are back calculated as
395 described in the Appendix. 1, where the reason that leads to different hydrological parameters for
396 each case is also explained.

397 The computed pore-water pressure changes for Boulder Creek are shown in Fig. 7a. We used the
398 same viscosity parameter μ for Minor Creek here but in order to better capture the quasi-
399 continuous motion of Boulder Creek we had to reduce the rheological parameter α to 0.15 (section
400 3.2 and Table 1). We then back-calculated the friction angle φ and found a value around 26° (see

401 Table 2) leads to satisfactory results in a form of continuous creep deformation (Fig. 7b). Our
 402 model is able to reproduce the overall landslide displacement of Boulder Creek after making these
 403 parameter adjustments.



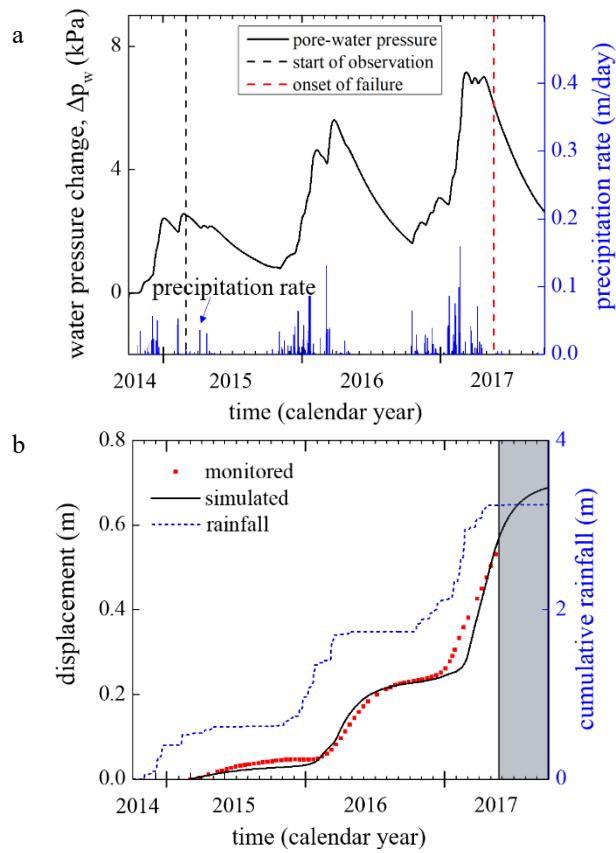
404

405 **Figure 7. Pore-water pressure change, rainfall, and displacement of Boulder Creek landslide during 2015**
 406 **~2017. a) Pore-water pressure variation at sliding surface and the precipitation rate; b) monitored**
 407 **and simulated landslide movement time history and the cumulative rainfall, model parameters shown in Table 2.**

408 4.4 Mud Creek landslide

409 Finally, we tested our model's ability to capture the slow and episodic motion displayed by the
 410 Mud Creek landslide prior to its catastrophic collapse (Fig. 5). We modeled the period of slow-
 411 motion between February 28, 2015, and May 13, 2017, that was measured with InSAR data (see
 412 details in Handwerger et al., 2019). The landslide has an area of around 23 hectares prior to
 413 catastrophic failure, thickness of 20 m (measured after landslide collapse; see Warrick et al., 2019),

414 and average slope 32° (Warrick et al., 2019; Handwerger et al., 2019). Similar to the previous case,
 415 pore-water pressure changes (Fig. 8a) are simulated with the hydraulic model calibrated based on
 416 the procedures discussed in the Appendix. 1. Precipitation data from a rain-gauge (Fig. 8) located
 417 around 50 km from the landslide provided by the California Climate Data Archive were used as
 418 the surface boundary condition.



419

420 **Figure 8. Pore-water pressure change, rainfall, and displacement of Mud Creek landslide during 2014 ~2017.**
 421 a) Simulated pore pressure variation at sliding surface and the precipitation rate. b) Simulated landslide
 422 movement time history and measured cumulative rainfall. The left boundary of the shaded rectangle represents
 423 the occurrence of catastrophic acceleration. Our model is not able to capture runaway instability and predicts
 424 a return to slow motion (black line inside gray shaded region).

425 We find that our hybrid rheological model can overall predict the landslide behavior using a value
 426 of $\alpha=0.7$, which is between those used for the Minor Creek and the Boulder Creek sites. Notably,
 427 we find that the back-calculated friction angle value is around 49° . This high value is because Mud

428 Creek is steep and thick (i.e., high initial stress ratio), and initial water level located near the ground
429 surface (leads to high pore-water pressure). In this context, the initial basal pore-water pressure
430 computed from stationary flow condition within an infinite slope is around 140 kPa, which is
431 higher than typical conditions observed at other sites and used in soil laboratory testing. In fact,
432 with an initial pore-water pressure around 20 kPa (induced by a water level around 2 m above the
433 sliding surface) as monitored from shallower landslides located in KJf (Finnegan et al., 2021;
434 Iverson and Major, 1987; Schulz et al., 2018), a much smaller friction angle would be back-
435 calculated (around 34°). Further validation of this value is provided in the Discussion section.

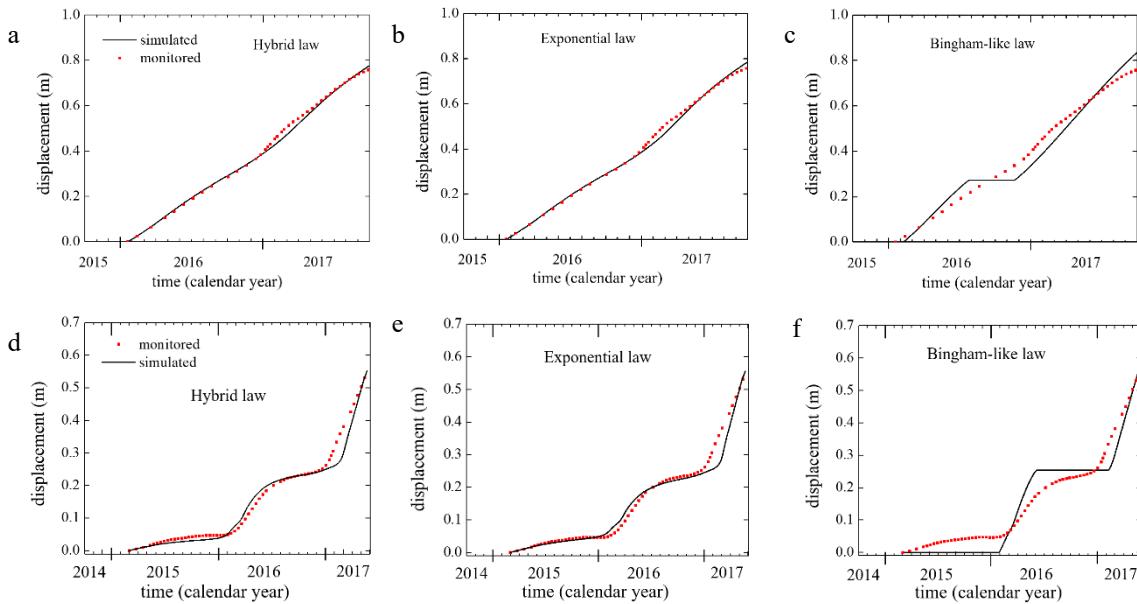
436 Although our model cannot describe the runaway acceleration of the landslide, we allowed our
437 simulations to continue to show what our model would have predicted for Mud Creek. Fig. 8b
438 shows that a deceleration are predicted after May 20, when catastrophic runaway acceleration
439 occurred. We show this to highlight a key limitation of our model framework and we outline plans
440 to improve this model in the future in the Discussion section below.

441 **5 Discussion**

442 In this paper, we developed a new model to describe the motion of slow-moving landslides driven
443 by precipitation. Our new model incorporates landslide activation under both pre-yield and post-
444 yield scenarios, which is an advance over commonly used viscoplastic models. The model can be
445 used to describe distinct types of landslide motion from episodic to quasi-stable sliding movements
446 with simple parameter calibration.

447 Viscoplastic models have been used to interpret landslide creeping movement broadly. Most
448 previous studies have used a Bingham-like rheological law (Fernandez-Merodo et al., 2014;
449 Oberender and Puzrin, 2016), which ignores the viscous creeping before the material yield surface

450 is approached. However, earthen materials are found to experience viscosity under the elastic
 451 domain (di Prisco and Imposimato, 1996; Sekiguchi, 1984), and therefore models need to account
 452 for this non-negligible deformation. Our analysis based on the InSAR data also suggested that
 453 some of the areas within active slow-moving landslides were creeping even when materials were
 454 in this elastic regime. With this motivation, we developed a new Hybrid rheological model (Eq. 6)
 455 to account for the deformations. Most notably, taking pre-yield viscosity into account can
 456 significantly improve simulation of landslide movement. To show the model improvement when
 457 taking pre-yield viscosity into account, the Boulder Creek and Mud Creek landslides (where pre-
 458 yield movement are observed as explained) are selected to run computations with the three
 459 rheological laws. The calibrated parameters (Table 3) are similar for each case using different
 460 model.



461
 462 **Figure. 9 Comparison of the Simulation of Boulder Creek and Mud Creek landslides using different rheological**
 463 **models. Boulder Creek displacement simulated using Hybrid law (a), exponential law (b), and Bingham-like**
 464 **law (c). Mud Creek simulated using Hybrid law (d), Exponential law (e), and Bingham-like law (f).**

465 Fig. 9a~b and 9d~e shows that, models using the exponential and Bingham rheological laws can
 466 capture both Mud Creek and Boulder Creek landslide creep movement satisfactorily. However, if

467 the Bingham-like law is used, then during the dry season the simulated landslide stops moving,
 468 which does not agree with the monitored displacement (Fig. 9c and Fig. 9f). In these case studies,
 469 both our hybrid rheology and the exponential rheology can lead to accurate results within the
 470 simulated periods of time. However, when dealing with higher subsequent precipitation, the
 471 exponential law will lead to much higher acceleration compared to our rheological model. The
 472 field observations show that annual maximum velocity of slow-moving landslide in our studied
 473 area varied insignificantly (Handwerger et al., 2013). Therefore, our hybrid model can be a better
 474 candidate to simulate earthen material behaviors.

475 **Table 3. Model parameters**

Model parameters	Hybrid (Boulder)	Exponential (Boulder)	Bingham-like (Boulder)	Hybrid (Mud)	Exponential (Mud)	Bingham-like (Mud)
α (-)	0.15	0.10	0.05	0.70	0.50	0.57
μ (kPa*s) ⁻¹	2.1E-8	2.1E-8	2.1E-8	2.1E-8	2.1E-8	2.1E-8
φ (°)	26.1	26.5	26.0	48.5	48.7	48.3

476
 477 We found that back-calculated friction angle values were higher, especially for Mud Creek, than
 478 those typically reported from lab measurements at landslide sites in KJf (Keefer and Johnson,
 479 1983; Iverson, 2005; Schulz et al., 2018). Our back-calculated friction values differ from these lab
 480 values for a few reasons. First, the back-calculated values account for large variations in landslide
 481 material properties at the field-scale known to the KJf. In fact, in lab tests by Roadifer et al., 2009,
 482 which measured the friction angle as a function of block-in-matrix percent, showed that the friction
 483 angle ranged from 20 to more than 50 degrees, increasing as the block-in-matrix proportion
 484 increased. Second, high friction angles are required to maintain force balance when there are steep

485 slopes, large landslide thickness, and high assumed pore-water pressures (e.g., Mud Creek). In
486 clay-rich slopes relatively high values of back-calculated friction angle may also partly reflect the
487 consolidation history of the material and the consequent nonlinearity of its strength envelope (Shi
488 et al., 2017). Lastly, we assumed that the landslide shear zone material had zero cohesion. This
489 assumption is reasonable because most of the earthen materials from landslide shear zones have
490 experienced significant displacement, which are likely to have rendered cohesive strength
491 contributions negligible. However, if the material has non-negligible cohesion, this would in part
492 offset the friction angle strength needed to maintain force balance.

493 Our computational process is data-driven, which means that one site of parameters from a case
494 study cannot be used directly to other cases although the landslide materials are located in the same
495 geological unit (KJf). It is not a surprising result as the landslides are distinct from the viewpoint
496 of topography, average slope angle (15° to 38°); and depth of sliding surface (6-40 m). Some local
497 conditions are also distinct site by site, such as the landslide size (Handwerger et al., 2013; Keefer
498 and Johnson, 1983) and rainfall conditions. In addition, the KJf material properties can also be
499 substantially different (Keefer and Johnson, 1983; Nereson, 2018).

500 One of the major benefits of predicting the landslide movement using viscoplastic models is that
501 they can describe post-failure landslide motions. This provides an advantage over most
502 elastoplastic models which lack unique solutions in post-failure scenarios (e.g., Puzrin, 2012), thus
503 cannot be used to quantify landslide creep movement behaviors. However, several studies have
504 shown that the viscosity of some slow-moving landslide materials is negligible, especially under
505 the small dynamic range of motion exhibited by slow-moving landslides (e.g., Schulz et al., 2018;
506 Iverson, 2020). Further complicating the issue, there is often a large discrepancy (more than three
507 orders of magnitude) between viscosity values obtained from laboratory tests and the ones gathered

508 from case study parameter back calculations (Angeli et al., 1996; Van Asch et al., 2007). These
509 large differences make it challenging to develop models with predictive capabilities. These prior
510 studies indicate that viscosity might not be solely sufficient to interpret slow-moving landslide
511 behaviors. There are other considerations that can result in rate-dependent properties and therefore
512 be used to describe post-failure motion such as thermo-mechanical interactions (Alonso et al.,
513 2016; Veveakis et al., 2007) and shear dilatancy (Hutchinson, 1986; Iverson et al., 2005; Chen and
514 Buscarnera, 2022), which are not considered in this paper. In reality all of these factors may be
515 important in controlling the landslide behavior.

516 Given these discrepancies, we suggest that the viscoplastic parameters back calculated for field
517 data may be more relevant than those measured on small lab samples. In addition, the permeability
518 of material from Minor Creek landslide (Iverson and Major, 1987) varied across 5 orders of
519 magnitude from 1.6×10^{-5} to 3×10^{-10} m/s also suggested to back calculate this parameter from the
520 range to capture the overall field-scale landslide behaviors.

521 **6 Conclusions**

522 Here we present a new model framework to simulate both the changes in subsurface pore-water
523 pressure driven by precipitation and the dynamics of slow-moving landslides. Our hydrological
524 model accounts for water mass diffusion across heterogeneous slope profiles. Similar to previous
525 work, we found that our simple 1D diffusion model can capture pore-water pressure variations that
526 are consistent with ground-based monitoring data.

527 We then used our hydrologic simulations as an input to drive our landslide model. We simulated
528 the sliding behavior of three real landslides using a new hybrid viscoplastic model. We found that
529 a hybrid viscous nucleus combined the benefits of a post-yield Bingham-like rheology that is

530 commonly used to model landslides, and a pre-yield creep that can describe precursory landslide
531 deformation. Our results show that the hybrid rheology is able to capture a variety of delayed
532 landslide movements observed at the three landslide sites in the California Coast Range. Although
533 a complete assessment of spontaneous transitions to catastrophic acceleration requires some other
534 factors such as thermo-mechanical interactions, progressive coalescence of discrete failure
535 surfaces, or a fully coupled hydro-mechanical formulation, which are not addressed in this work.
536 The analyses discussed here provide a versatile strategy to interpret velocity changes in creeping
537 landslides governed by rainfall by incorporating explicitly both the hydraulic and mechanical
538 effects responsible for their manifestation, thus offering a springboard for future extensions
539 including coupled pore-water pressure feedbacks and post-failure dynamics.

540

541

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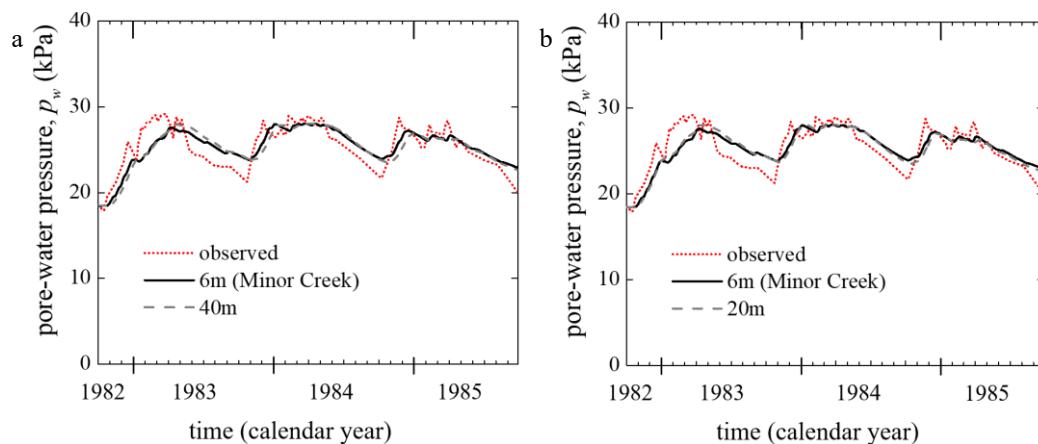
549

550 **Appendix. Back calculation of the hydraulic parameters for Boulder Creek and Mud Creek**

551 **Landslides**

552 Since there is no ground-based monitoring of pore-water pressure changes for Boulder Creek and
553 Mud Creek landslides, we modeled the hydraulic response based on observations from the Minor
554 Creek site. To do this, we assumed that the sliding surface of three studied cases each experienced
555 similar hydrological changes driven by rainfall. Our assumption is justified based on the
556 hydrological observations of KJf (Iverson & Major, 1987; Schulz et al., 2018; Hahm et al., 2019
557 Finnegan et al., 2021).

558 To calibrate the model parameters for Boulder Creek and Mud Creek, we use the observed data
559 from Minor Creek. We then adjusted the modeled landslide thickness for Minor Creek to back-
560 calculate the hydraulic parameters required to match the observations assuming a 20 m thick (Mud
561 Creek) and 40 m thick (Boulder Creek) landslide.



562

563 **Figure A1. Calibration of Boulder Creek and Mud Creek hydraulic parameters. a) Simulation of Minor Creek**
564 **with 40 m depth. b) Simulation of Minor Creek with 20 m depth.**

565 Fig. A1a shows that when we change the thickness of Minor Creek to 40 m (i.e., Boulder Creek
566 thickness), the k_s (saturated permeability) increases to 4.6E-6 m/s and S_s (storage coefficient)
567 changes to $0.03 m^{-1}$ to simulate a similar hydrological response. Similarly, as depicted in Fig. A1b,

568 when we change the thickness of Minor Creek to 20 m (i.e., Mud Creek thickness) we must change
569 the k_s 4.6E-6 m/s and S_s 0.07 m^{-7} to obtain a similar result. The deeper the infiltrated depth, the
570 higher the diffusivity that is required to obtain the same hydrological response (Eq. 1).

571

572 **Conflicts of interests**

573 With the present all the authors declare that they do not have any financial and/or personal conflict
574 with other people or organizations that could inappropriately influence or bias their work.

575

576 Sincerely yours,

577 Xiang Li

578 Alexander Handwerger

579 Giuseppe Buscarnera

580

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