

2021-05

# Hydro-sediment-morphodynamic processes of the baige landslide-induced barrier Lake, Jinsha River, China

Li, J

<http://hdl.handle.net/10026.1/17643>

---

10.1016/j.jhydrol.2021.126134

Journal of Hydrology

Elsevier

---

*All content in PEARL is protected by copyright law. Author manuscripts are made available in accordance with publisher policies. Please cite only the published version using the details provided on the item record or document. In the absence of an open licence (e.g. Creative Commons), permissions for further reuse of content should be sought from the publisher or author.*

1           **Hydro-Sediment-Morphodynamic Processes of the Baige Landslide-induced**  
2                                   **Barrier Lake, Jinsha River, China**

3  
4                   Ji Li<sup>a, b</sup>, Zhixian Cao<sup>a\*</sup>, Yifei Cui<sup>c</sup>, Xuanmei Fan<sup>d</sup>, Wenjun Yang<sup>e</sup>,

5                                   Wei Huang<sup>e</sup>, Alistair G. L. Borthwick<sup>f</sup>

6  
7           <sup>a</sup> *State Key Laboratory of Water Resources and Hydropower Engineering Science, Wuhan*  
8           *University, Wuhan 430072, China;*

9           <sup>b</sup> *Zienkiewicz Centre for Computational Engineering, College of Engineering, Swansea*  
10           *University, Swansea SA1 8EN, UK;*

11           <sup>c</sup> *State Key Laboratory of Hydrosience and Engineering, Tsinghua University, Beijing*  
12           *100084, China;*

13           <sup>d</sup> *State Key Laboratory of Geohazard Prevention and Geoenvironment Protection, Chengdu*  
14           *University of Technology, Chengdu 610059, China;*

15           <sup>e</sup> *Changjiang River Scientific Research Institute, Wuhan 430010, China;*

16           <sup>f</sup> *Institute for Infrastructure and Environment, The University of Edinburgh, Edinburgh EH9*  
17           *3FG, UK.*

18           \*Corresponding author, Zhixian Cao, email address: zxcao@whu.edu.cn

19  
20           **Highlights:**

- 21           ● The 2018 Baige landslide-induced barrier lake on the Jinsha River is investigated
- 22           ● The whole process is well reconstructed by a single 2D model for the first time
- 23           ● An artificial flood channel effectively alleviated downstream flood risk
- 24           ● Grains drive water during landslide dam formation, but water governs the outburst
- 25           ● Effects of upstream inflow discharge and initial landslide volume are revealed
- 26

27 **Abstract**

28 A large landslide impacting a river may cause a multi-phase chain of hazards, comprising  
29 landslide-generated waves, inundation as a barrier lake develops upstream a landslide dam  
30 arising from rapid sediment deposition, and downstream flooding due to barrier lake outburst.  
31 Two major landslides (each of volume  $\sim 10^7 \text{ m}^3$ ) occurred successively on 10<sup>th</sup> October and  
32 3<sup>rd</sup> November 2018 at Baige village, Tibet, China. Both landslides led to a natural dam that  
33 completely blocked the Jinsha River, along with a barrier lake filled with upstream river  
34 inflow. Although the first barrier lake breached naturally, a significant quantity of residual  
35 material from the first landslide dam was left behind without being eroded. After the second  
36 landslide occurred, a flood channel was urgently constructed to facilitate an artificial breach  
37 of the barrier lake as it formed. The Baige landslide-induced barrier lake is unique as  
38 triggered by two successive landslides and outbursts a mere five weeks apart. Here a  
39 computational investigation is presented of the hydro-sediment-morphodynamic processes of  
40 the Baige barrier lake, using a recent 2D double layer-averaged two-phase flow model. This  
41 is the first modelling study of the whole field and whole processes for the formation and  
42 outburst of a landslide-induced barrier lake as well as the resultant floods, without evoking  
43 presumptions on dam breach (which have prevailed for decades and bear much uncertainty).  
44 The computed results agree well with field observations in terms of landslide-generated  
45 waves, landslide dam morphology, stage and discharge hydrographs at the dam site and  
46 downstream flood hydrographs. The artificial flood channel is shown to be effective for  
47 alleviating downstream inundation. Water and grain velocities are demonstrated to be distinct,  
48 characterizing the primary role of grains in landslide dam and barrier lake formation and the  
49 dominant role of water in barrier lake outburst and the resultant flood. Relatively low inflow  
50 discharge and large initial landslide volume favour landslide dam and barrier lake formation,  
51 but delay the outburst and downstream flood. The present 2D double layer-averaged  
52 two-phase model holds great promise for assessing future landslide-induced multi-hazard  
53 chains in rivers, and informing mitigation and adaptation strategies.

54 **Keywords:** landslide dam; landslide-generated waves; barrier lake outburst; flood;  
55 hydro-sediment-morphodynamic processes; double layer-averaged two-phase flow model

56

## 57 **1. Introduction**

58        Landslides are common geophysical mass events in mountainous regions, especially  
59 those with deep, narrow valleys (Costa and Schuster, 1988; Ermini and Casagli, 2003). A  
60 landslide impacting a river often produces a multi-hazard chain comprising  
61 landslide-generated waves, a landslide dam, a barrier lake, a lake outburst, and resultant  
62 floods, leading to spatial-temporal amplification of hazard (Carpignano et al., 2009; Fan et al.,  
63 2019a). More specifically, when a subaerial landslide impacts a narrow river valley, large  
64 amplitude water waves and active sediment transport can be generated. Due to rapid  
65 deposition of a huge amount of sediment, a landslide dam forms as the riverbed rapidly  
66 aggrades and then emerges from the water (Costa and Schuster, 1988; Van Asch et al., 1999).  
67 The resulting water waves may trigger further landslides and/or collapses of the opposite  
68 riverbank, entraining additional sediment into the river and facilitating landslide dam  
69 formation. As a consequence of sustained upstream inflow and significant water-level rise,  
70 the water impounded by a landslide dam usually creates a barrier lake, which may inundate  
71 upstream land and infrastructure. Owing to its rather loose structure, a landslide dam formed  
72 by granular materials can easily burst, leading to destructive downstream floods. Such  
73 outburst floods from a barrier lake consist of highly mobile water-sediment mixtures, capable  
74 of traveling long distances (sometimes beyond 100 km) at high velocity (exceeding 10 km/hr).  
75 These events can cause high numbers of casualties and severe infrastructural damage (Ermini  
76 and Casagli, 2003; Shang et al., 2003; Dai et al., 2005), due to their sudden onset, high  
77 magnitude discharge, long runout distance, and their tendency to flow along existing river  
78 channels where humans and property are concentrated (Carrivick, 2010; Cui et al., 2013).

79 Typical historical examples include the landslide dam outburst events in June 1786 at  
80 the Dadu River, Sichuan, China, which is reported to have caused more than 100,000  
81 fatalities (Dai et al., 2005; Lee and Dai, 2011), in October 1999 at the Poerua River, New  
82 Zealand (Davis et al., 2007), in April-June 2000 at the Yigong Zangpo River, Tibetan, China  
83 (Delaney and Evans, 2015), in May 2008 at Tangjiashan, Sichuan, China due to the  
84 Wenchuan earthquake (Xu et al., 2009), and in October 2018 at Yarlung Tsangpo River in  
85 Tibetan Plateau, China due to ice-avalanche (Chen et al., 2020). More recently, two major  
86 landslides occurred successively on 10 October and 3 November 2018 (Fan et al., 2019b),  
87 which created a natural dam that completely blocked the Jinsha River, followed by a barrier  
88 lake filled by upstream runoff. On 12 October, the first barrier lake breached naturally with a  
89 peak discharge of about 10,000 m<sup>3</sup>/s (Cai et al., 2019). The residual landslide dam was  
90 replenished with sediment from the second landslide on 3 November, forming a larger barrier  
91 lake than the first. On 11 November, following the urgent construction of a flood channel, the  
92 second barrier lake breached artificially with a peak discharge of 33,900 m<sup>3</sup>/s.

93 Modelling the whole-process chain of a landslide-induced barrier lake flood is important  
94 for two reasons. First, knowledge of the chain is useful in assessing the hazard and risk of  
95 potential future landslide-induced barrier lake flood events. This is both salient and timely,  
96 noting that climate change is promoting increased instability of high mountain slopes and has  
97 accelerated increasing trends in the amount, intensity, and occurrence frequency of extreme  
98 precipitation (Donat et al., 2013), which are likely to trigger more landslides. Second, the  
99 whole-process chain is key to improving our understanding of such earth surface processes  
100 that are prohibitively difficult to observe in nature owing to their sheer complexity. Physically,

101 a typical landslide-induced multi-hazard chain involves two distinct but intertwined processes:  
102 aggradation through sediment deposition during landslide dam and barrier lake formation;  
103 and degradation induced by sediment erosion during a barrier lake outburst and the  
104 subsequent floods. Previous studies have mostly focused on one or two components of the  
105 whole-process chain, whereas little work has been done on the whole-process chain  
106 modelling.

107       Landslide dam and barrier lake formation represent the first part of the whole-process  
108 chain. In general, existing models for resolving landslide dam and barrier lake formation can  
109 be divided into two categories: discrete models and continuum models. Typical discrete  
110 models like Smoothed Particle Hydrodynamics - SPH (Shi et al., 2016; Xu et al., 2020) and  
111 Materials Point Method two-phase models (Bandara and Soga, 2015) can be directly used for  
112 modelling landslide dam and barrier lake formation. Other examples include coupled Discrete  
113 Element Method landslide models and fluid flow models based on computational fluid  
114 dynamics (Zhao et al., 2017), Lattice-Boltzmann Method (Leonardi et al., 2016), as well as  
115 coupled Discontinuous Deformation Analysis and SPH models (Wang et al., 2017, 2019). Yet,  
116 excessive computational costs preclude applications of these models to real field-scale cases.  
117 As far as continuum models are concerned, although 3D models are available (e.g., Hu et al.,  
118 2020), double layer-averaged models hold great promise for resolving landslide dam and  
119 barrier lake formation due to their ability to represent the two-way coupling between  
120 landslide motions and water flows (Abadie et al., 2012) and to achieve a sensible balance  
121 between theoretical integrity and applicability (Li et al., 2019). It should be emphasized that  
122 double layer-averaged models are automatically applicable when there is only a single-layer

123 flow, either clear-water flow or water-sediment mixture flow. Recently, a 2D double  
124 layer-averaged two-phase flow model (Li et al., 2020) has been proposed for landslide dam  
125 and barrier lake formation, which employs one set of layer-averaged single-phase flow  
126 equations to describe the upper clear-water flow layer and a second set of layer-averaged  
127 two-phase flow equations to describe the subaerial or subaqueous water-sediment mixture  
128 flow layer. This model incorporates multiple grain size, inter-phase and inter-grain size  
129 interactions, unlike previous double layer-averaged models that involve a single-phase flow  
130 assumption and assume a single grain size (e.g., Skvortsov and Bornhold, 2007; Liu and He,  
131 2016; Si et al., 2018; Li et al., 2019) and that ignore mass exchange with the bed, sediment  
132 mass conservation and steep slope effect (e.g., Skvortsov and Bornhold, 2007; Si et al., 2018).  
133 It is noted that the double layer-averaged single-phase model by Liu and He (2016)  
134 incorporated mass exchange with the bed, but incorrectly added a term for actual momentum  
135 exchange with the bed (see statement by Cao et al. 2017), and assumed constant sediment  
136 concentration, which is in conflict with the sediment mass conservation law.

137 Overtopping flow with subsequent dam erosion is the most common trigger for a barrier  
138 lake outburst (Costa and Schuster, 1988). Over the past few decades, substantial effort has  
139 been devoted to improving the understanding of the mechanisms underpinning a barrier lake  
140 outburst and the subsequent flood (Cao et al., 2011b). Particular attention has been paid to  
141 landslide dam breaching due to its governing role in the generation and propagation of the  
142 downstream flooding. According to ASCE/EWRI (2011), dam breach models can be  
143 categorized as parametric models, simplified physically based models, and detailed  
144 physically based models. Parametric models are derived purely from data collected from a

145 series of documented breaching events (e.g., Walder and O'Connor, 1997; Xu and Zhang,  
146 2009; Peng and Zhang, 2012). Simplified physically based models, such as NWS BREACH  
147 (Fread, 1988), WinDAM (Temple et al., 2005), HR BREACH (Morris et al., 2009), DABA  
148 (Chang and Zhang, 2010), and DLBreach (Wu, 2013), predict outflow hydrographs from a  
149 breaching dam. The accuracy of such predictions hinges upon predefined model assumptions  
150 (most critically, weir flow assumption) and physical input parameters. Detailed physically  
151 based models (Wang and Bowles, 2006a, b; Faeh, 2007; Wang et al., 2008; Cao et al., 2011b,  
152 c; Wu et al., 2012; Huang et al. 2012; Li et al. 2013) incorporate the physical mechanisms of  
153 a dam breach. Discharge and stage hydrographs as well as breach development can be  
154 resolved without predefining or constraining the evolution process. It is noted that in order to  
155 predict outburst downstream floods, it is customary for the aforementioned parametric and  
156 simplified physically-based dam breach models to be integrated with flood routing models,  
157 e.g., FLO-2D (O'Brien et al., 1993), HEC-RAS (USACE, 2016), and BASEMENT (Vetsch et  
158 al., 2018). In contrast, detailed physically based models can resolve flow and sediment  
159 transport throughout the entire computational domain (ASCE/EWRI, 2011).

160 Integrated modelling refers to individual modelling of specific processes within a  
161 whole-process chain, with sub-model outputs of a single process used at each subsequent step  
162 as input to the next process sub-model. A general disadvantage of this approach is that  
163 transitions between different processes are not straightforward (Worni et al., 2014), and one  
164 sub-model output may not exactly fit the required input for the next sub-model. Concurrently,  
165 integrated modelling hinges upon the capability of the sub-models involved. Liu and He  
166 (2018) tried to model the whole-process chain of the Yigong landslide by integrating a double

167 layer-averaged single-phase model (Liu and He, 2016) for landslide dam and barrier lake  
168 formation and a conventional single layer-averaged single-phase model (e.g., Cao et al., 2004)  
169 for a dam breach and subsequent flood routing. Fan et al. (2020a) conducted an integrated  
170 modelling study on the Baige landslide-induced multi-hazard chain using a MassFlow  
171 sub-model for landslide movement, a DABA sub-model (Chang and Zhang, 2010) for dam  
172 breaching, and a one-dimensional HEC-RAS sub-model for downstream flood routing.  
173 Inevitably, the integrated model is constrained by the capability of each sub-model. For  
174 instance, the MassFlow sub-model is a single layer-averaged single-phase flow model for  
175 landslide movement, and so cannot resolve landslide-induced waves and barrier lake  
176 formation that involve strong interactions between landslide motion and river flow.

177 Overall, a single state-of-the-art model that properly couples all physical processes is the  
178 way forward (Worni et al., 2014). In this regard, a 2D double layer-averaged two-phase flow  
179 model appears particularly attractive, noting that such a model has previously been applied  
180 successfully to landslide dam and barrier lake formation caused by a landslide impacting a  
181 river (Li et al., 2020), and that its single-phase predecessor was applied for a barrier lake  
182 outburst and subsequent flood (Li et al., 2013). Here the hydro-sediment-morphodynamic  
183 processes of the Baige landslide-induced multi-hazard chain are investigated using the model  
184 of Li et al. (2020). First, we aim to benchmark the model against field observations of  
185 landslide-generated waves, landslide dam morphology, stage and discharge hydrographs in  
186 2018. The role of water and grains in the whole processes is evaluated. Second, we aim to  
187 unravel the effects of inflow discharge and landslide volume on the multi-hazard chain as  
188 unstable rock mass clusters in the source area of the Baige landslides may fail in the future,

189 characterizing potential for river damming and flooding (Fan et al., 2020a). To the authors'  
190 knowledge, this is the first whole-field and whole-process modelling study of the Baige  
191 landslide-induced multi-hazard chain using a single physically based model (Li et al., 2020),  
192 unlike existing studies on a part of the whole-process chain (Hu et al., 2020; L. Zhang et al.,  
193 2019; Zhong et al., 2020; Fan et al., 2020a). Most notably, the present work does not involve  
194 presumptions regarding the onset of landslide dam outburst and of the breach/scour pattern  
195 and discharge estimation by analogy to weir flow, which have prevailed for several decades  
196 and bear excessive uncertainty.

197

## 198 **2. Baige barrier lake**

199 In 2018, the Jinsha River, the upper course of the Yangtze River, was blocked by two  
200 successive landslides that occurred on 10 October and 3 November (Fig. 1). At 22:00 on 10  
201 October (Beijing time, UTC + 8 throughout the paper), a large landslide occurred on the right  
202 bank of the Jinsha River, at Baige village, located at the border between Sichuan Province  
203 and Tibet Autonomous Region, China (98°42'17.98" E 31°4'56.41" N). The first landslide  
204 had a total material volume of about 27.5 million m<sup>3</sup> (Cai et al. 2019), the majority of which  
205 formed a landslide dam of bed length ~1500 m and crest width ~ 700 m (Fig. 2a), aligned  
206 stream-wise and transverse respectively with the river. The dam crest elevation ranged from  
207 3005 m above mean sea level at the left bank to 2931 m at the right bank. This landslide dam  
208 completely blocked the Jinsha River, for the first time in recent history. As the inflow  
209 discharge reached 1680 m<sup>3</sup>/s (Cai et al., 2019), the water level rose rapidly, leading to the

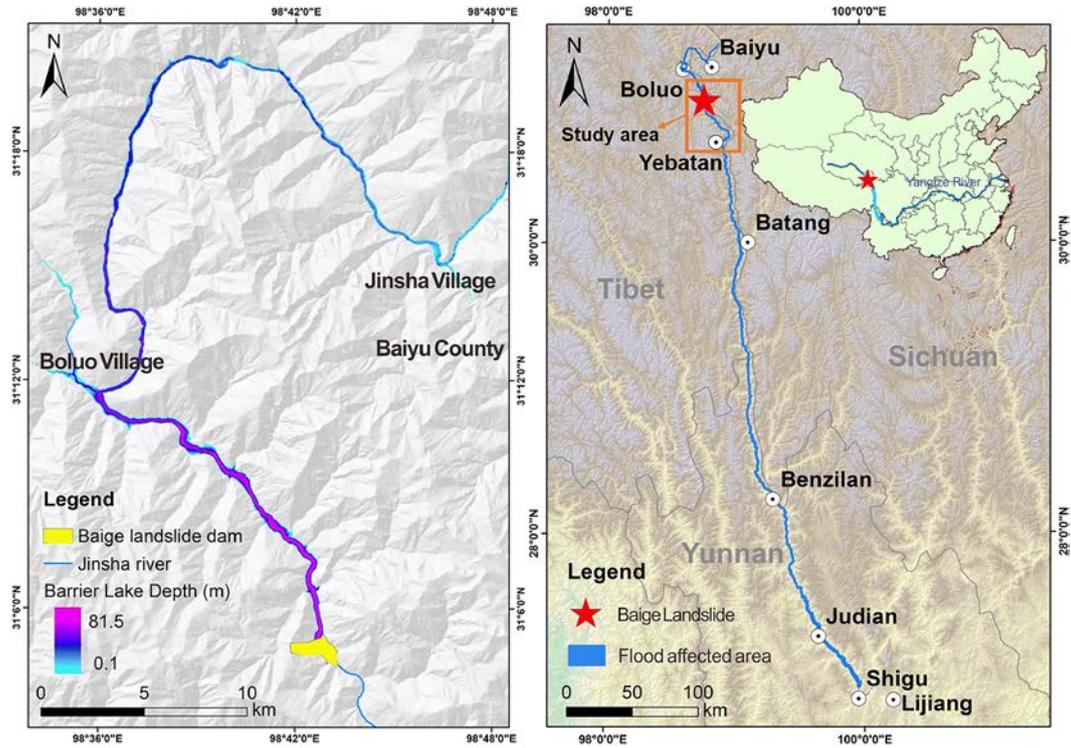
210 formation of a barrier lake, called the “10.10” Baige barrier lake. The landslide dam  
211 overtopped naturally at 17:30, 12 October, and underwent breaching for about 21 hrs (Fig.  
212 2b). Details of the breaching process have been documented as follows. The breaching flow  
213 discharge was less than 100 m<sup>3</sup>/s before 20:00 on October 12. By 00:45 on October 13, the  
214 water level in the barrier lake reached a maximum of 2932.7 m above mean sea level,  
215 corresponding to a water storage volume of 290 million m<sup>3</sup>. The overflow increased  
216 significantly after 01:00 on October 13. At 06:00 on October 13, the breaching flow peaked  
217 at about 10,000 m<sup>3</sup>/s (Cai et al. 2019). Afterwards, the breaching flow gradually attenuated  
218 and returned to base flow by about 14:00 on October 13. The natural breach of the “10.10”  
219 Baige barrier lake resulted in a flood that caused huge damage to towns in its downstream  
220 path. Many houses, roads, and bridges were damaged or even destroyed, and more than  
221 20,000 people had to be evacuated.

222 About 3 weeks after the natural breach of the first barrier lake, a second landslide, caused  
223 by reactivation of residual material left behind by the first landslide, occurred at the same site  
224 at 17:15 on 3 November. Landslide material was deposited on the earlier natural breaching  
225 channel and blocked the Jinsha River once again (Fig. 3a). The second landslide had an initial  
226 volume of about 3.5 million m<sup>3</sup>, and an additional entrainment volume of about 8.5 million  
227 m<sup>3</sup>. The average height of the new landslide dam was 50 m higher than its predecessor, and  
228 its lowest crest elevation was approximately 2966 m above mean sea level. With an incoming  
229 flow discharge of about 800 m<sup>3</sup>/s, the water level increased continuously, forming the  
230 so-called “11.03” Baige barrier lake. As the second landslide had raised the overall height of  
231 the landslide dam, the threat posed by the second barrier lake was higher than by the first lake.

232 To mitigate flood risk, an artificial flood channel, 220 m long, 15 m deep, 42 m top width,  
233 and 3 m bottom width, was constructed at the lowest crest of the second landslide dam,  
234 reducing its bed elevation to 2951 m (Fig. 3b). With this flood channel in place, the landslide  
235 dam overtopped at 04:45 on 12 November, and the breaching process lasted over 50 hrs (Fig.  
236 3c, d). The peak dam breach flow discharge reached 33,900 m<sup>3</sup>/s at 18:20 on 12 November.  
237 At the dam site, the discharge returned to a base flow level by 08:00 on 14 November. The  
238 outburst flood destroyed many bridges along the Jinsha river including the Old Zhubalong  
239 Jinsha Bridge connecting a key highway between Sichuan and Tibet, inundated numerous  
240 towns, and led to the urgent evacuation of over 100,000 people.

241 The study area of the present work extends from approximately 6 km upstream of the  
242 Baige landslide dam site to Yebatan gauging station (54 km downstream of the Baige  
243 landslide dam site), and includes a ~ 60 km long reach of the Jinsha river (Fig. 1).

244



245

246

**Fig. 1.** Location of Baige barrier lake, Jinsha River, China (adapted from Fan et al., 2020a):

247

(a) upstream areas inundated by barrier lake; (b) towns affected by downstream flooding (the

248

orange box indicates the study area).

249



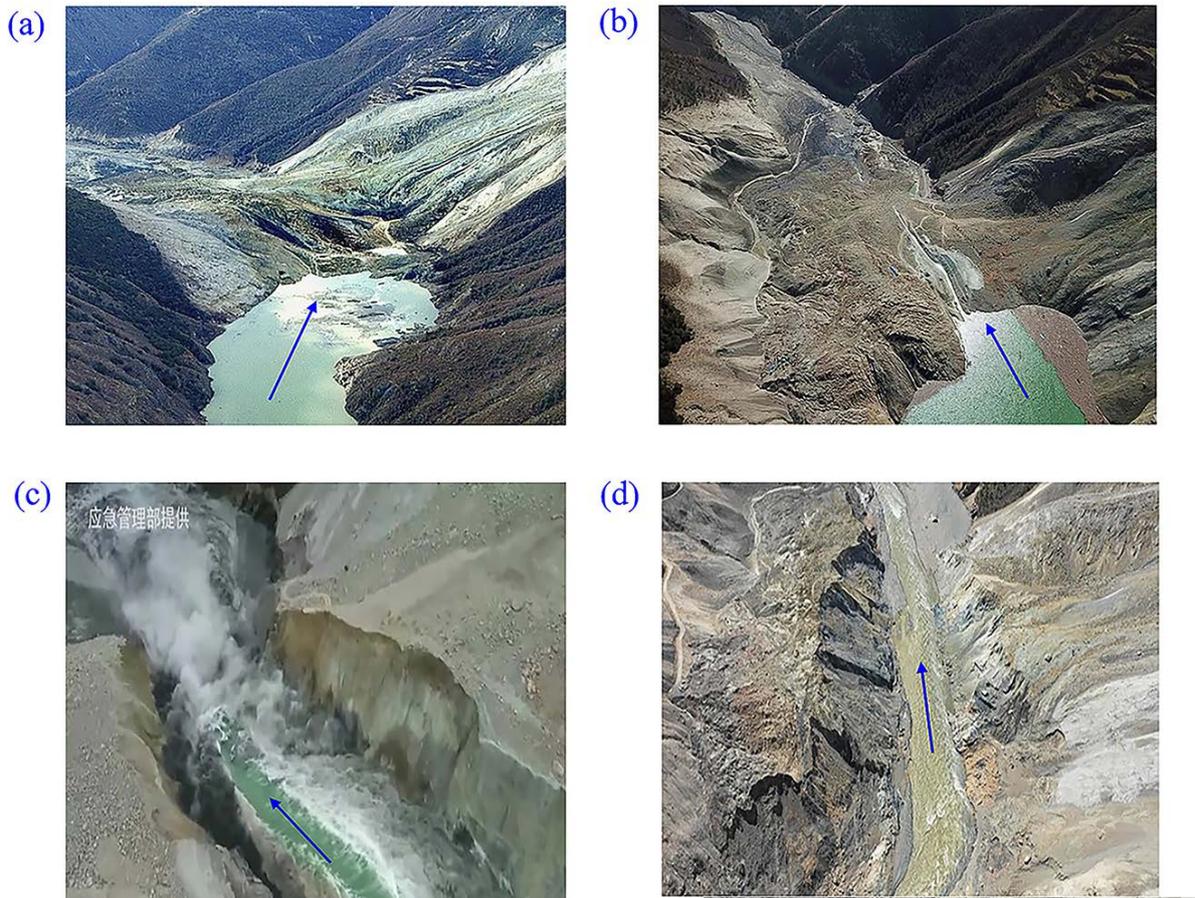
250

251

252

253

**Fig.2.** “10.10” Baige barrier lake: (a) formation; (b) after breaching. (photo courtesy of Chinanews.com).



254

255

256

257

**Fig. 3.** “11.03” Baige barrier lake: (a) formation; (b) with artificial flood channel; (c) during breaching; (d) after breaching (photo courtesy of a CCTV.com; b Red Star News; c Ministry of Emergency Management of China; d L. Zhang et al., 2019).

258

### 259 **3. Modelling method**

#### 260 *3.1. Mathematical model*

261

262

263

264

265

A recent state-of-the-art 2D double layer-averaged two-phase model (Li et al., 2020) is used to resolve the whole-process chain concerning the Baige events, commencing from landslide-generated waves, to landslide dam and barrier lake formation as the landslide impacted the Jinsha river, and thence to the outburst of the barrier lake and subsequent flood propagation downstream.

266 Li et al. (2020) provide a detailed description of the 2D double layer-averaged two-phase  
267 flow model equations, model closure, and the numerical algorithm. Briefly, the model has  
268 been constructed according to continuum mechanics principles, and explicitly incorporates  
269 multiple grain sizes, sediment mass conservation, mass exchange with the bed, and interphase  
270 and inter-grain size interactions. To close the model, a set of relationships is introduced to  
271 determine shear stresses, water entrainment, interaction forces, and sediment exchange fluxes.  
272 It should be noted that all the closure relations used in the double layer-averaged two-phase  
273 flow model have been established in the general field of shallow water  
274 hydro-sediment-morphodynamics. Although the model incorporates first-order factors, such  
275 as gravitation, resistance, inter-phase and inter-grain size interactions, higher-order factors  
276 such as non-Newtonian liquid viscous stress (Pudasaini, 2012), viscous particle resuspension  
277 (Reeks and Hall, 2001) and shear-induced particle migration (Morris, 2009), are yet to be  
278 included in the model.

279

### 280 *3.2. Model set-up*

281 In this study, in order to improve computational efficiency, the whole-process chain  
282 concerning the Baige barrier lake events of 2018 has been divided into Phase I: “10.10”  
283 Baige barrier lake event, and Phase II: “11.03” Baige barrier lake event. This is reasonable  
284 given the more than three-week gap between the two events. For Phase I, the pre-sliding bed  
285 topography was reconstructed using a 15m-resolution DEM (Digital Elevation Model). The  
286 total duration of the Phase I simulation was 72 hrs, from 22:00 on 10 October to 22:00 on 13  
287 October. For Phase II, the bed morphology resulting from the first event was used as the

288 initial bed topography. The total duration of the Phase II simulation was 260 hrs, from 17:15  
289 on 3 November to 13:15 on 14 November. For each phase, time  $t = 0$  s coincided with the  
290 instant that the relevant landslide began to occur. The position and thickness of the initial  
291 landslide body were estimated from the post-landslide field survey (Cai et al., 2019). Water  
292 level elevation and velocity prior to landslide were determined by maintaining a constant  
293 base flow at the inlet boundary. From the landslide deposit investigation by L. Zhang et al.  
294 (2019), the bulk porosity  $p = 0.45$ , median grain size  $d_{50} \approx 10$  mm, grain density  $\rho_s =$   
295  $2700 \text{ kg/m}^3$ . According to the grain size distribution measured by L. Zhang et al. (2019), the  
296 sediment mixture was separated into two size fractions:  $d_1 = 1$  mm (60%) and  $d_2 = 20$  mm  
297 (40%), with mean diameter  $d_m$  of 8.6 mm.

298 The friction angle  $\delta = 35^\circ$ , the Manning coefficients for bed roughness  $n_b = 0.04$   
299  $\text{m}^{-1/3} \text{ s}$ , interface roughness  $n_w = 0.01 \text{ m}^{-1/3} \text{ s}$ , the empirical weighting parameter  $\varphi = 0.65$ ,  
300 and the modification coefficient  $\phi = 1$  were calibrated to the observed landslide dam  
301 morphology and breaching flow discharge after the first landslide, and then directly applied  
302 to the second barrier lake event. The inflow discharge of clear water ( $Q_i$ ) was kept constant  
303 throughout each phase of the simulation, i.e.  $Q_i = 1680 \text{ m}^3/\text{s}$  for Phase I, and  $Q_i = 800$   
304  $\text{m}^3/\text{s}$  for Phase II. The clear water velocity and layer thickness at the inlet were determined by  
305 the method of characteristics. At the outlet, either the method of characteristics was used to  
306 obtain updated values of the flow variables under subcritical flow conditions, or zero flow  
307 variable gradients imposed for supercritical flows (Liang and Borthwick, 2009). Within the  
308 time period considered, the landslides did not reach the computational boundaries, and so the  
309 landslide boundary conditions were simply set at the initial static state. The overall

310 dimensions of the computational domain were 35 km × 20 km, and a fixed uniform mesh of  
311 spatial increment 20 m was adopted. The  $x$ - and  $y$ - directions are aligned north-south  
312 and east-west, respectively. The Courant number,  $Cr$ , was set to 0.4.

313 To quantify the error of a numerical solution as compared with measured data, the  
314 non-dimensional discrepancy is defined based on the  $L^1$  norm

$$315 \quad L_f^1 = \frac{\sum_{i=1}^N \text{abs}(\bar{f}_i - \hat{f}_i)}{\sum_{i=1}^N \bar{f}_i} \quad (1)$$

316 where the symbol  $f$  represents physical variables such as bed deformation thickness and  
317 flow discharge;  $N$  is the number of measured data;  $\bar{f}$  denotes numerical solution,  
318 whereas  $\hat{f}$  represents measured data.

319

## 320 **4. Results**

### 321 *4.1. Phase I: the “10.10” Baige barrier lake event*

322 First, the Phase I “10.10” Baige barrier lake event is reconstructed, commencing from  
323 landslide-generated waves, and landslide dam and barrier lake formation, through to the  
324 barrier lake outburst and downstream flood propagation. Multiple anticipated scenarios  
325 concerning effects of inflow discharge and initial landslide volume are considered, and  
326 sensitivity analysis to evaluate the effects of bed friction coefficient  $\tan \delta$  and Manning  
327 roughness coefficient  $n_b$  are conducted.

328

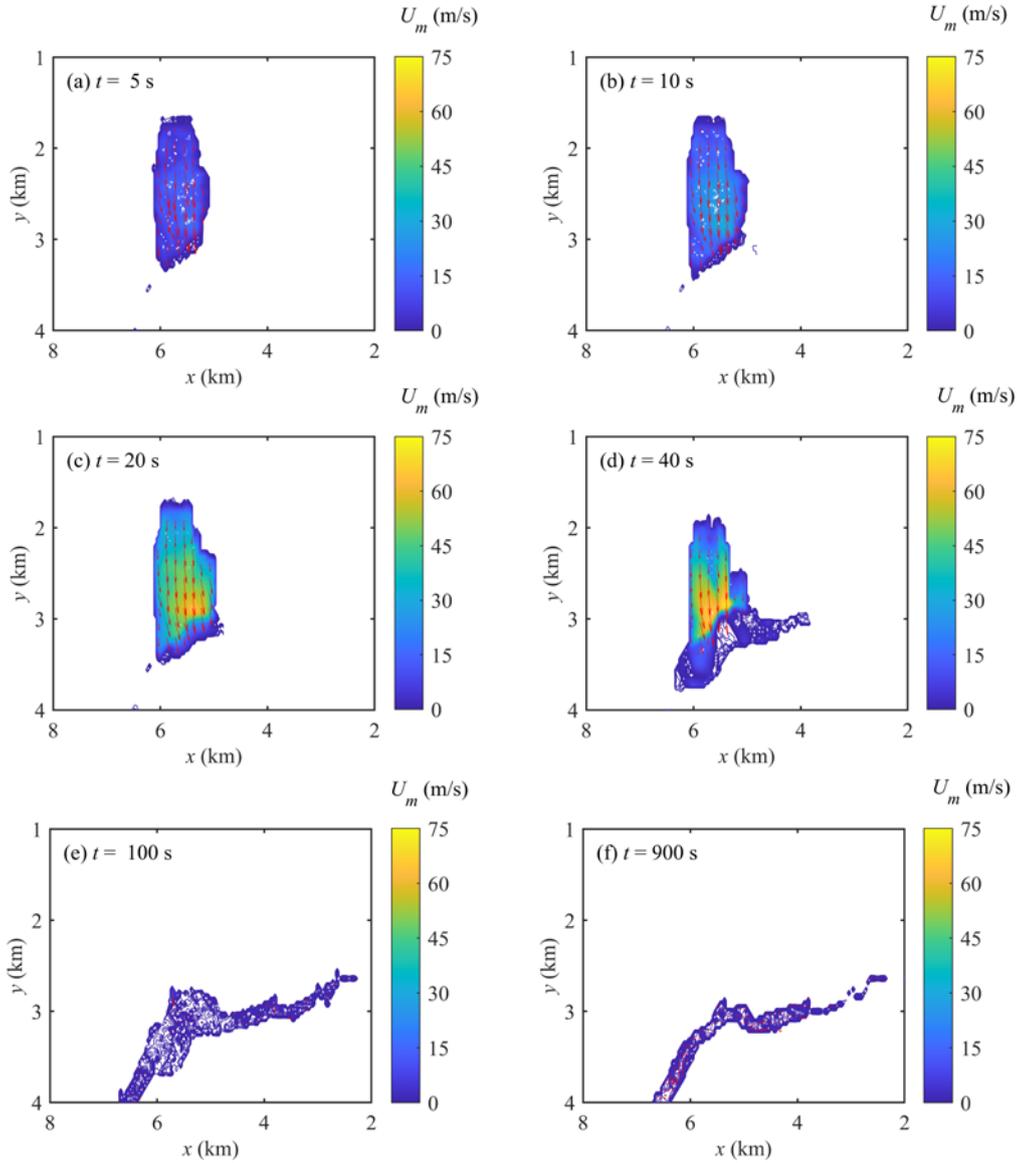
329 *4.1.1. Landslide movement and wave generation*

330 According to the field survey and analysis of broadband seismograms undertaken by Z.  
331 Zhang et al. (2019), the peak velocity of the landslide during its runout was recorded at the  
332 nearest seismological station within 100 s. Fig. 4 shows the predicted evolution of landslide  
333 velocity  $U_m$  ( $=\sqrt{u_m^2 + v_m^2}$ , where  $u_m$  and  $v_m$  are the layer-averaged horizontal velocity  
334 components of the water-sediment mixture in the landslide in the  $x$ - and  $y$ -directions.  
335 After initiation, the sliding mass accelerates eastwards down the hillslope alongside the  
336 Jinsha river, and first arrives at the water surface at  $t = 20$  s when the landslide front has a  
337 speed of approximately 62 m/s and has not yet reached its maximum (Fig. 4c). The rear of the  
338 landslide continues to push the front further into the river channel. By  $t = 40$  s, most of the  
339 landslide material has impacted the river and is generating waves; meanwhile, the direction of  
340 travel of the landslide material is diverted downstream with a maximum sliding mass speed  
341 of approximately 72 m/s (Fig. 4d). The predicted maximum speed is close to alternative  
342 computed results ( $\approx 75$  m/s) by Hu et al. (2020) using Flow-3D software. Subsequently, the  
343 landslide gradually decelerates, resulting in decreased landslide speed and thickness due to  
344 rapid deposition of the landslide material (Fig. 4(e-f)). Notably, at  $t = 100$  s, landslide  
345 movement has almost come to a halt with its maximum speed falling below 2 m/s, echoing  
346 the findings from the field survey and analysis of broadband seismogram signals (Z. Zhang et  
347 al., 2019). By  $t = 900$  s, the landslide thickness has almost vanished, indicating that most of  
348 the landslide material has been deposited on the riverbed and a landslide dam formed.

349 After the landslide impacts the Jinsha River, the river surface is disturbed, generating  
350 large waves. These landslide-generated waves are initially forced by inertia of the high-speed

351 sliding mass, with water displaced soon after the sliding mass crashes into the river channel.  
352 Along with the sliding mass, the generated waves tend to run up the opposite bank in the  
353 direction of the landslide run-out. After a landslide-generated wave moves to its maximum  
354 elevation on the opposite bank, water then flows back into the watercourse. As evident in  
355 Table 1, the computed results provide a satisfactory match to field observations by Cai et al.  
356 (2019) of the maximum run-up elevation of the landslide-generated waves and the size of the  
357 area affected by the waves on the opposite bank. Fig. 5 shows predicted water level  
358 hydrographs at Points A, B, and C along the river course, which indicate the propagation of  
359 landslide-generated waves downstream and upstream of the “10.10” Baige landslide in the  
360 Jinsha River. The hydrographs indicate that the waves propagate as bores with steep front and  
361 flattening rear. The maximum elevation of the water level at point B rise to 2950 m, exceeding  
362 the initial water surface by about 90 m. The maximum water level reaches 2919 m at point A  
363 and 2900 m at point C, indicating that the landslide-generated waves may produce more  
364 serious hazards in the downstream zone. The initial rises in water level at points B and C  
365 occur almost simultaneously, showing that the main entry position of the sliding mass is  
366 situated in the near upstream zone.

367



368

369 **Fig. 4.** Phase I “10.10” Baige landslide impacting Jinsha river: model predictions of landslide  
 370 velocity field at times  $t =$  (a) 5 s, (b) 10 s, (c) 20 s, (d) 40 s, (e) 100 s, and (f) 900 s.

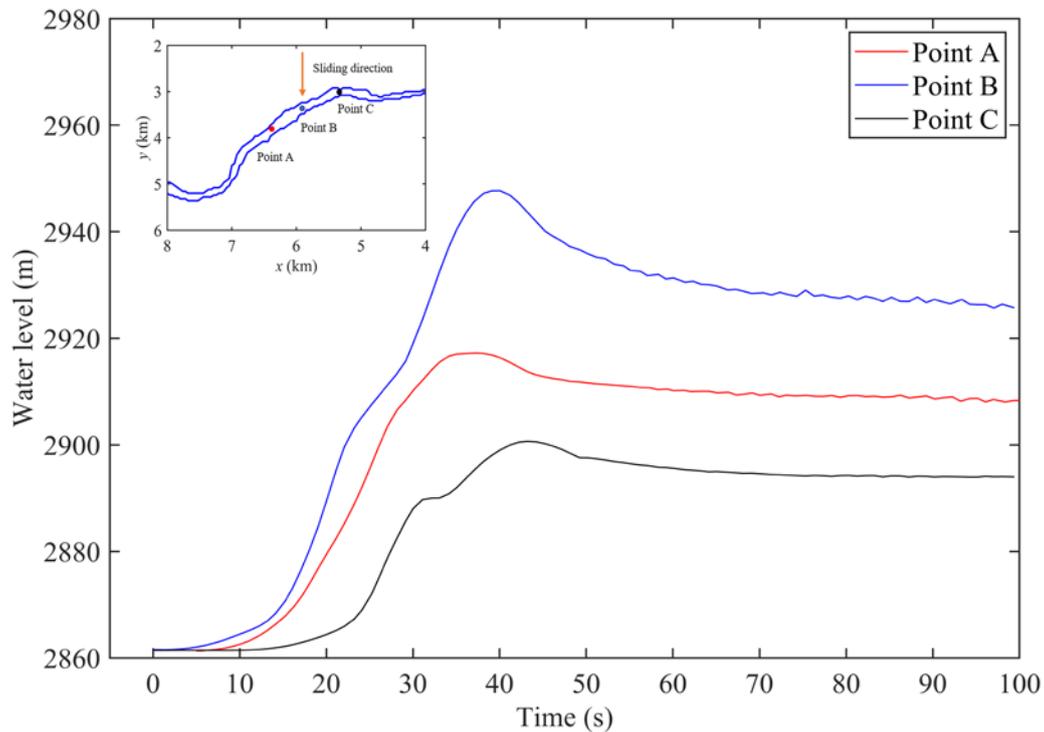
371

372 **Table 1** “10.10” Baige landslide-generated wave run-up on the opposite bank

Results	Computed	Measured
Maximum elevation (m)	3051.8	3065
Affected region	Length (m)	1500
	Area ( $10^4 \text{ m}^2$ )	37.6

373

\* Observed data from Cai et al. (2019)



374

375 **Fig. 5.** Phase I “10.10” Baige landslide-generated waves: predicted water level hydrographs  
 376 at three locations in the Jinsha river near Baige, Sichuan, China.

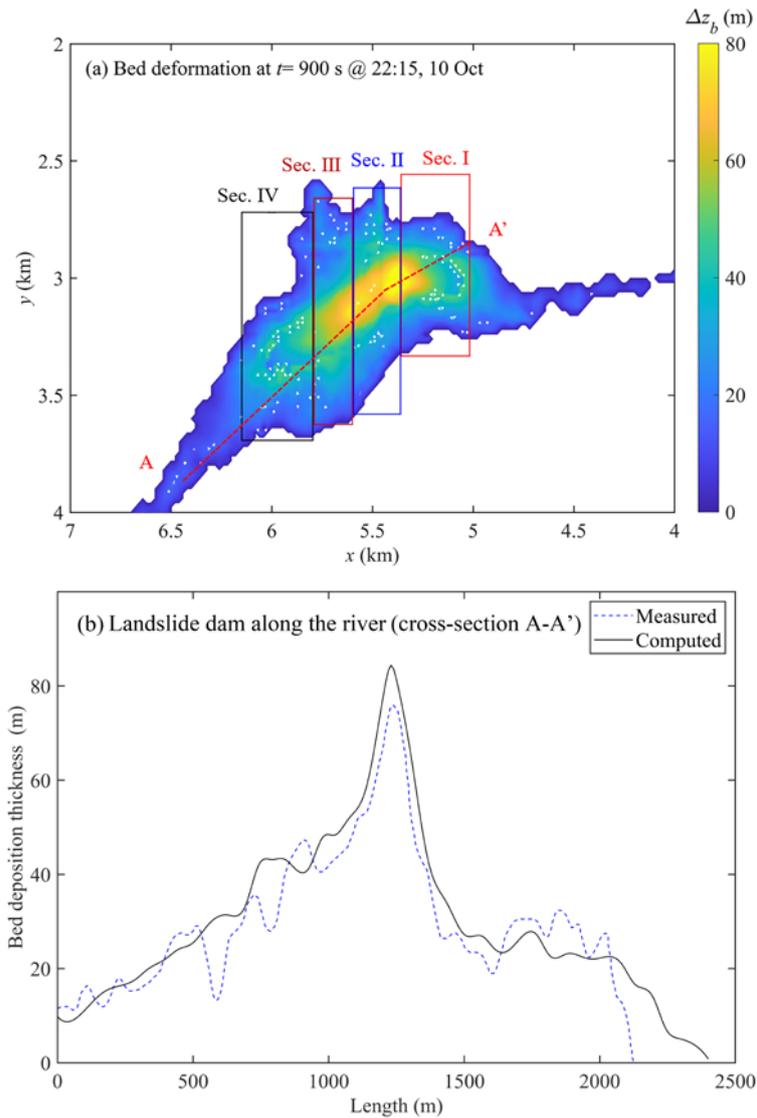
377

378 *4.1.2. Landslide dam and barrier lake formation*

379 Fig. 6(a) displays the landslide dam morphology, represented by deformation of the  
 380 original bed, at  $t = 900$  s. In general, the dam body is higher at the left bank than at the right  
 381 bank. The landslide dam body is divided into four longitudinal sections (I, II, III, and IV) in  
 382 the river flow direction, following Cai et al. (2019). Table 2 shows the consistent agreement  
 383 obtained between the computed and measured elevations above sea level and lengths of the  
 384 four longitudinal sections. Fig. 6(b) presents the predicted cross-section thickness profile at  
 385 A-A' (Fig. 6a) of the landslide dam along the river, along with measured data from Fan et al.  
 386 (2020a). Although discrepancies are appreciable between the present modelling and observed

387 data, the landslide dam morphology predicted by the present model is in good overall  
 388 agreement with the measured data. In particular, the computed maximum dam height is 84.2  
 389 m, slightly higher than the measured value of 81.4 m. Quantitatively, the value of the  $L^1$   
 390 norm for bed deposition thickness  $L_{bd}^1 = 12.45\%$

391



392 **Fig. 6.** “10.10” Baige landslide dam geometry: (a) bed deformation at  $t = 900$  s predicted  
 393 by present model; and (b) cross-section profile of landslide dam in the original river  
 394 stream-wise direction (A-A’): model prediction (solid line) and measured data from Fan et al.  
 395 (2020a) (dashed line).  
 396

397

398

**Table 2** Summary of “10.10” Baige landslide dam morphology

Section	Elevation (m)		Length (m)	
	Computed	Measured*	Computed	Measured*
I	2996~3012	2998~3005	410	412
II	2965~2978	2973~2977	220	206
III	2963~2981	2977	250	215
IV	2943~2953	2948~2951	450	421

399

\* Observed data from Cai et al. (2019)

400

401

402

403

404

405

406

407

408

409

410

411

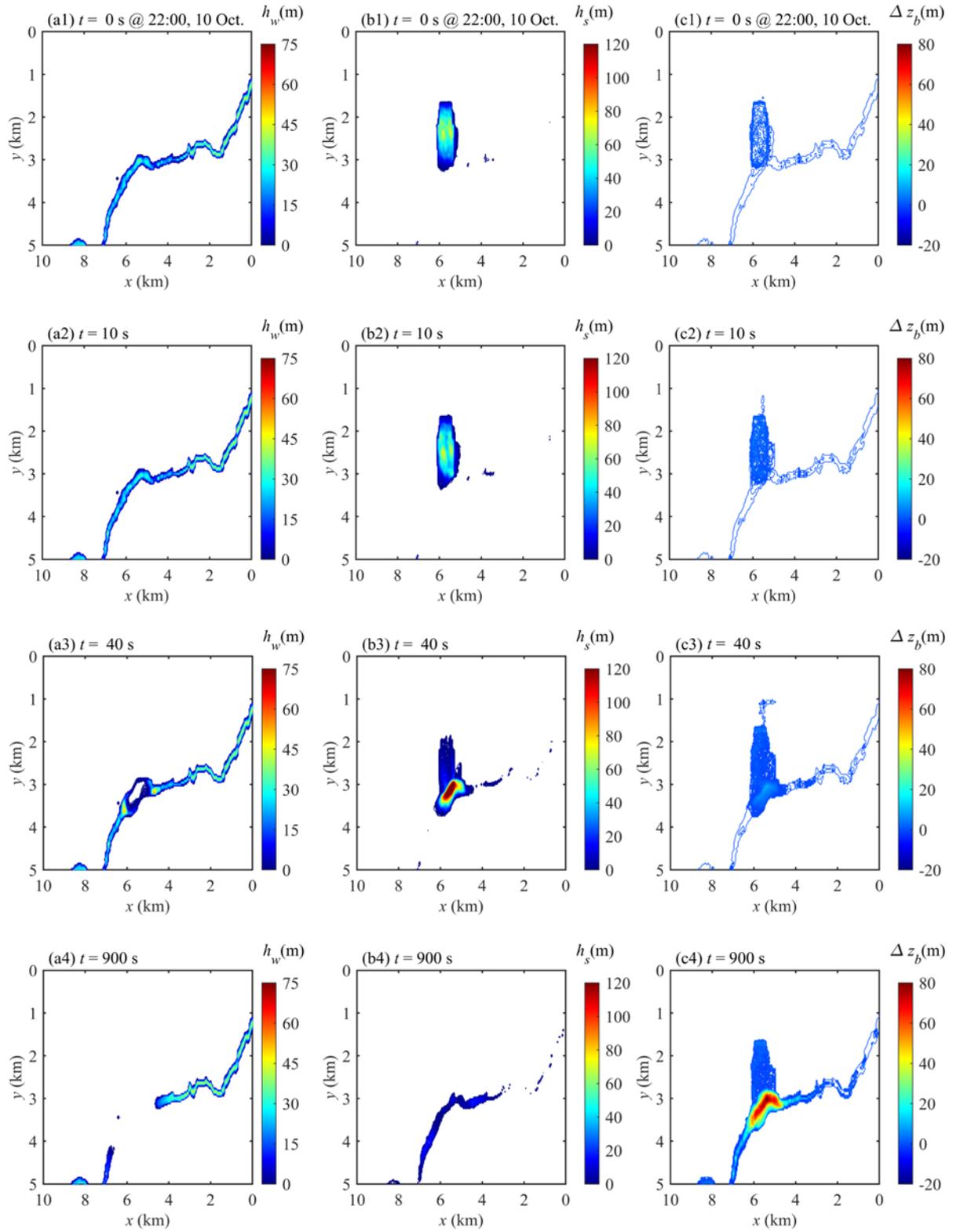
412

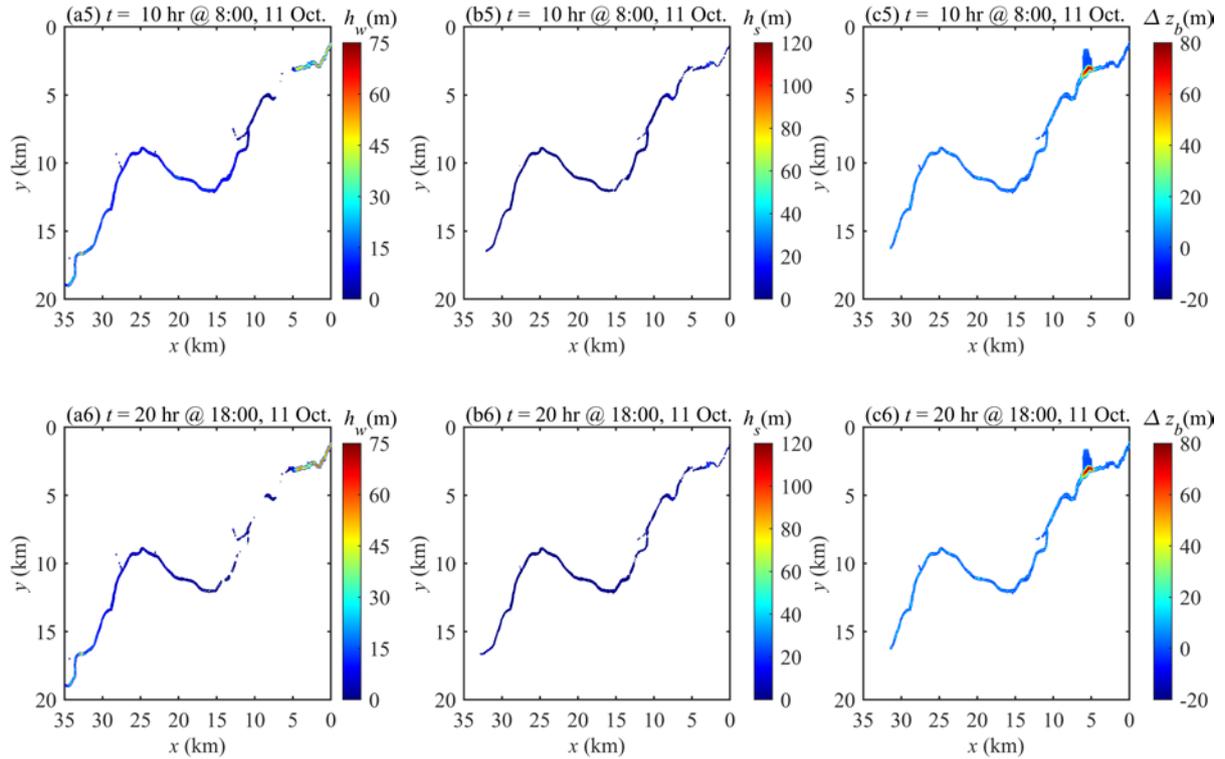
413

414

415

Fig. 7 shows the landslide dam and barrier lake formation process due to the “10.10” Baige landslide impacting the Jinsha river as the water layer depth  $h_w$ , landslide layer thickness  $h_s$ , and bed deformation  $\Delta z_b$  evolve with time. The landslide first accelerates down the hillslope ramp (Figs. 7 a1-a2, b1-b2), then directly crashing into the river, and forcing the water to run up the opposite bank while generating large water waves (Figs. 7 a3, b3 and c3). Later, most of the landslide material is rapidly deposited on the riverbed, forming a landslide dam (Figs. 7 a4, b4 and c4). Meanwhile, water waves significantly erode the opposite riverbank (Fig. 7 c4), entraining more sediment into the river and further facilitating landslide dam formation. Soon after the landslide dam forms, a barrier lake is created due to the river blockage, and the volume of this lake gradually increases thereafter due to the sustained upstream inflow, as shown in Figs. 7(a5 and a6). During this stage, waves propagate back and forth upstream of the dam, affected by a combination of the sustained river inflow and the sudden arrival of the dam. By contrast, waves downstream of the landslide dam exhibit one-way propagation downstream adding to riverbed erosion.





417

418 **Fig. 7.** “10.10” Baige landslide dam and barrier lake formation: (a1-a6) depth of water layer;  
 419 (b1-b6) landslide thickness; and (c1-c6) bed deformation.

420

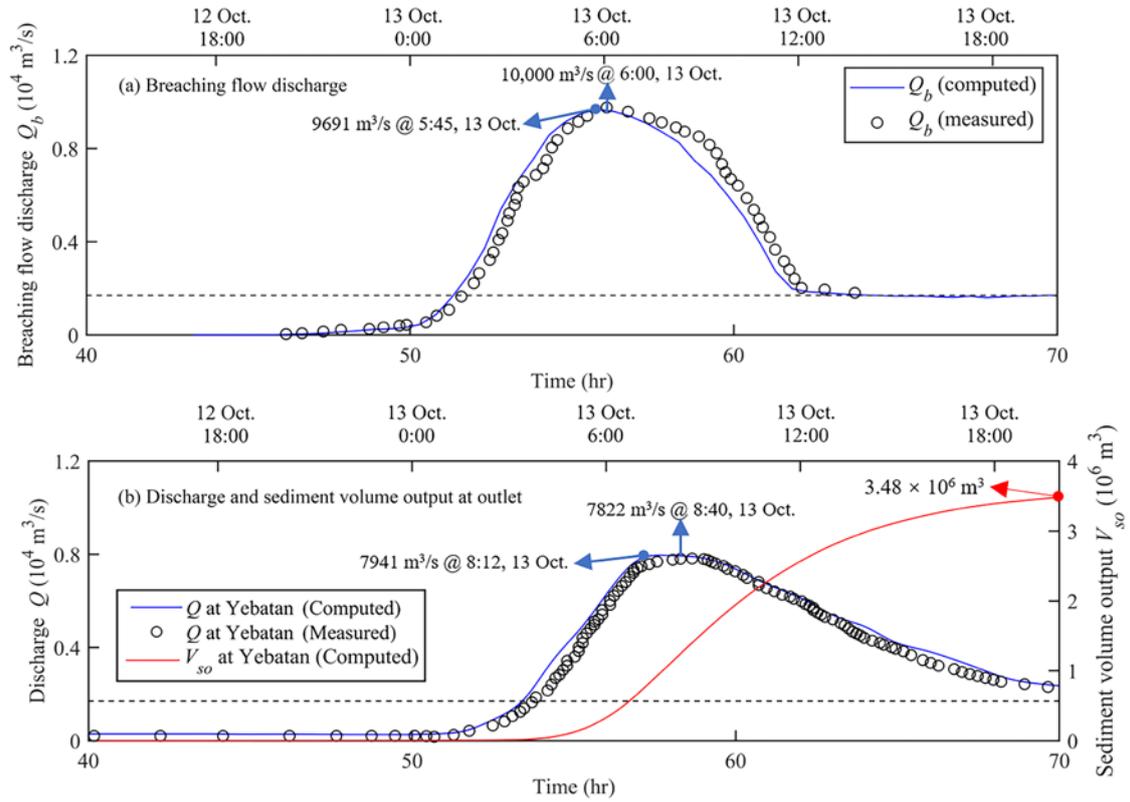
421 *4.1.3. Barrier lake outburst and the resultant flood*

422 The “10.10” Baige landslide dam was overtopped naturally at 17:30, 12 October. This  
 423 overtopping flow increased drastically at midnight (00:00, 13 October), reached a peak value  
 424 of approximately 10,000 m<sup>3</sup>/s at about 06:00 on 13 October, and returned to base flow at  
 425 14:30 on 13 October. Fig. 8(a) shows the excellent agreement obtained between the predicted  
 426 breach flow hydrograph with the observed data reported by Cai et al. (2019). The predicted  
 427 peak discharge of 9691 m<sup>3</sup>/s occurs at 05:45 on 13 October, and is slightly below the  
 428 observed peak of 10,000 m<sup>3</sup>/s and 15 mins earlier than the observed time (06:00 on 13  
 429 October). The present model offers improved accuracy over simplified physically-based  
 430 models (such as that of L. Zhang et al., 2019). Fig. 8(b) presents computed and measured

431 discharge hydrographs at the downstream gauging station at Yebatan, along with computed  
432 sediment volume output time series. Again, the model predictions closely match the measured  
433 data. It can be seen that the peak discharge is attenuated along the river. At Yebatan, the  
434 predicted peak discharge is 7941 m<sup>3</sup>/s at 8:12 on 13 October, whereas the observed maximum  
435 discharge is 7822 m<sup>3</sup>/s at 8:40 on 13 October. Thereafter, the discharge gradually reduces to  
436 base flow. By the end of “10.10” Baige barrier lake event, it is estimated that  $3.48 \times 10^6$  m<sup>3</sup> of  
437 sediments have been flushed downstream due to the outburst flood, thus the bulk aggradation  
438 in the river course between Baige dam site and Yebatan amounts to  $2.4 \times 10^7$  m<sup>3</sup> [=  $2.75 \times 10^7$   
439 m<sup>3</sup> (total volume of “10.10” Baige landslide) –  $3.48 \times 10^6$  m<sup>3</sup> (sediment volume output)]. The  
440  $L^1$  norms for breaching flow discharge hydrograph  $L_{Q_b}^1$  and flow discharge hydrograph at  
441 Yebatan gauging station  $L_{Q_y}^1$  are respectively 15.3% and 16.25%.

442 Fig. 9 presents the simulated time series of water levels at the barrier lake and several  
443 sites downstream of the landslide dam. Due to bursting of the barrier lake, its water level,  
444 indicated by the dashed line, decreases by over 27 m, which is consistent with the observed  
445 value in excess of 20 m reported by media. Water levels at locations downstream of the  
446 landslide dam site generally experience a sharp increase due to the arrival of the outburst  
447 flood and then a relatively flatter decrease with time. Similar to the peak discharge (Fig. 8),  
448 the amplitude of water level rise becomes increasingly attenuated with distance along the  
449 river (the value decreases from 28 m at a location 5 km downstream of the dam to 13.5 m at  
450 Yebatan).

451



452

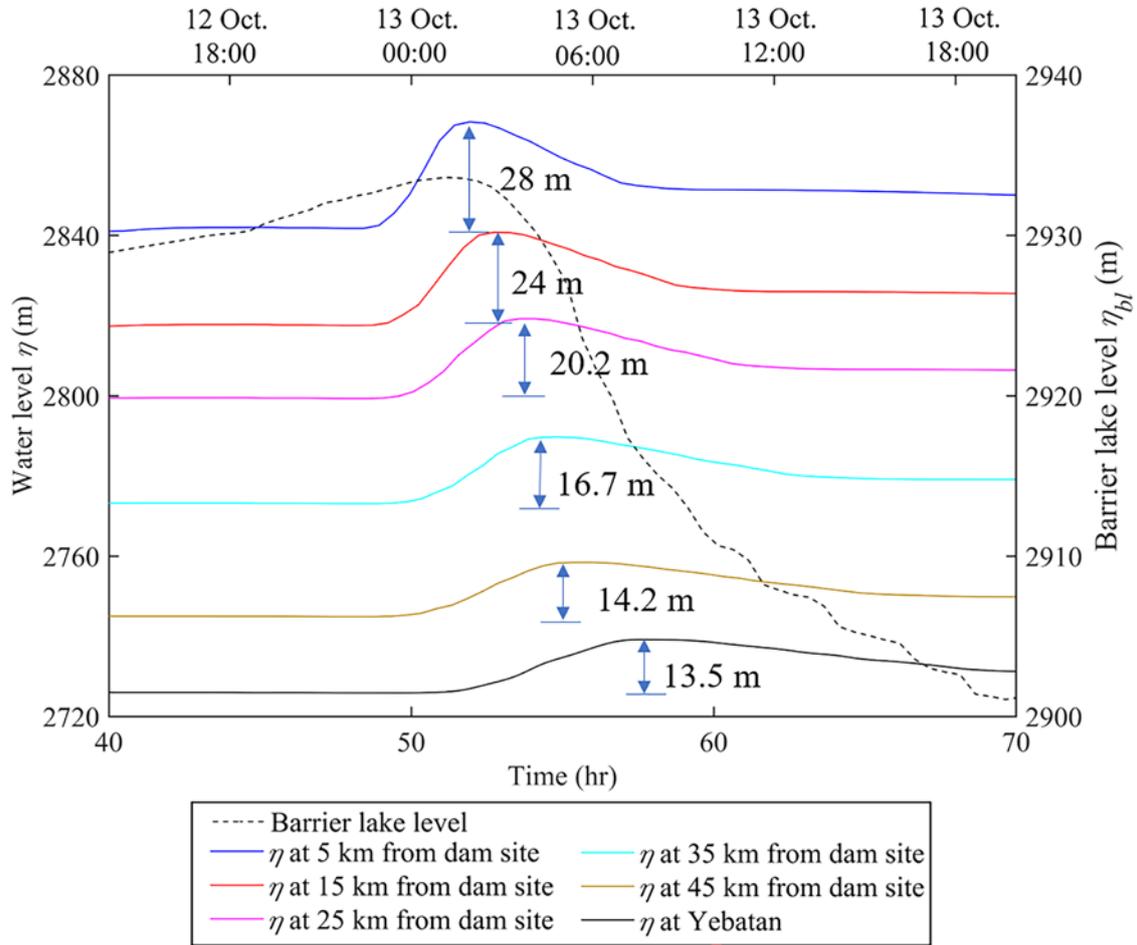
453

454

455

456

**Fig. 8.** (a) Breaching flow discharge hydrograph and (b) flow discharge hydrograph and sediment volume output time series at the Yabatan gauging station: model predictions (solid lines) and measured data from Cai et al. (2019) (open black circles).



457

458

**Fig. 9.** Water level time series at the barrier lake and selected sites downstream of the “10.10” Baige landslide dam.

459

460

461

462

463

464

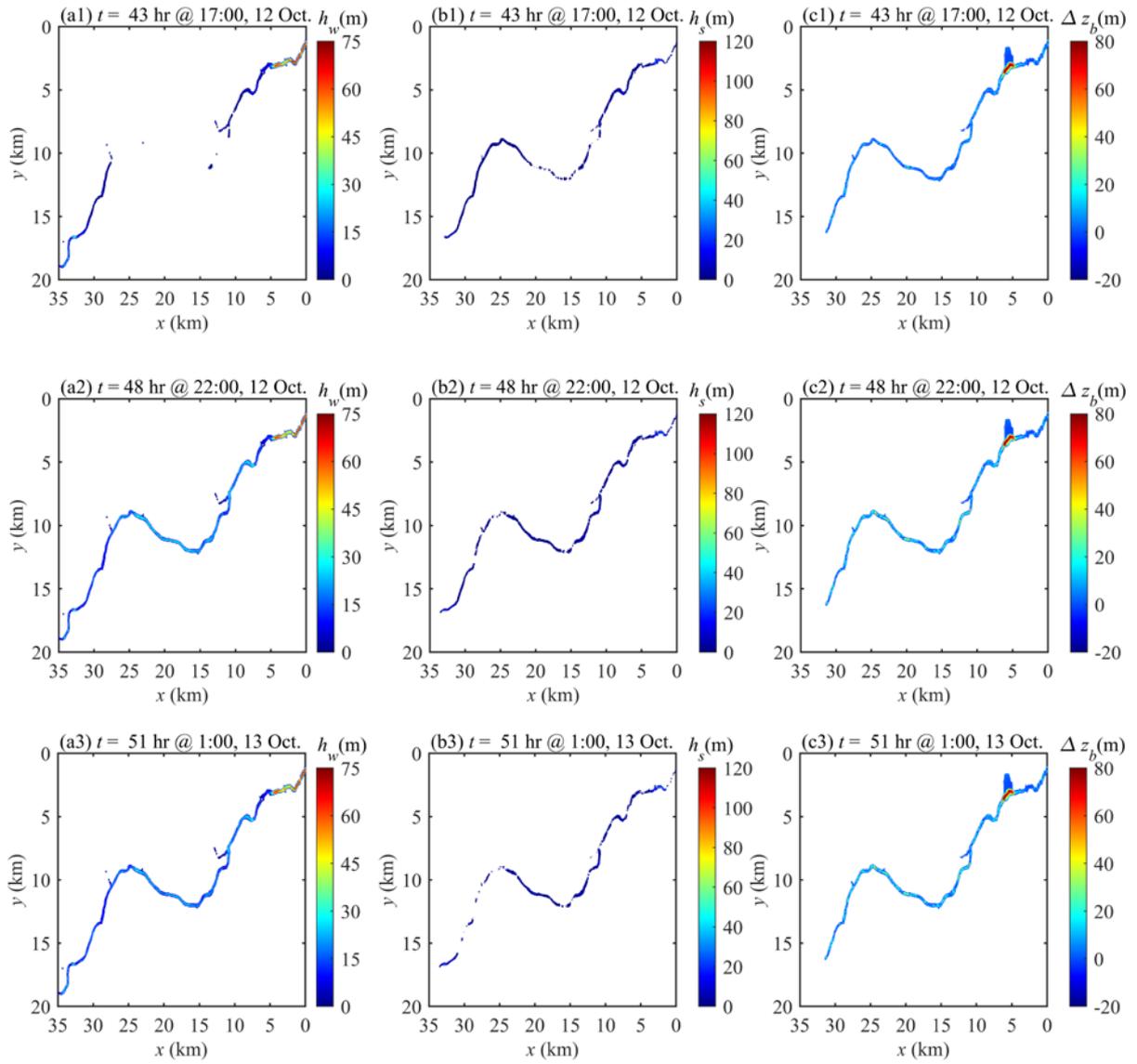
465

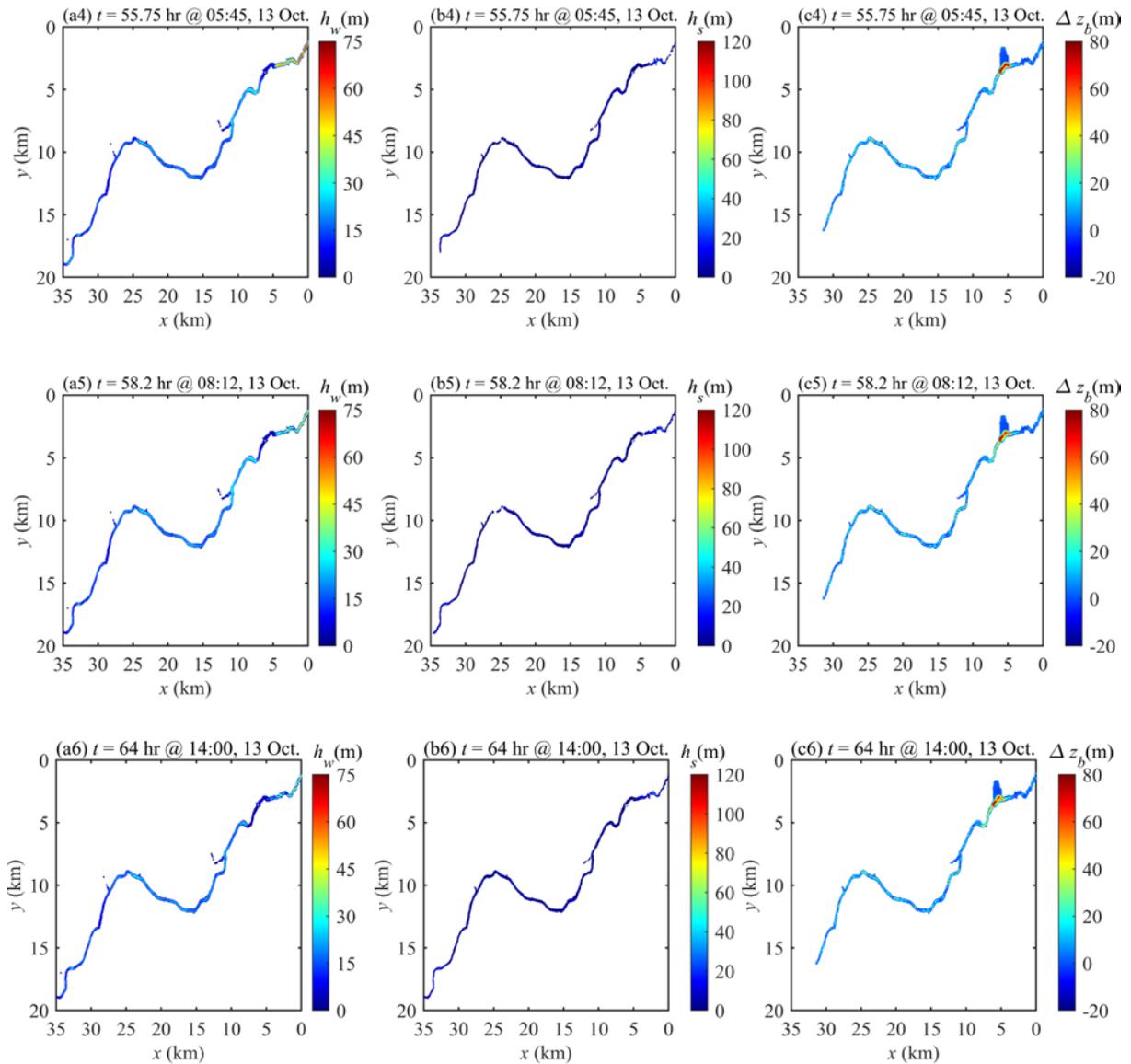
466

467

Fig. 10 presents contour plots of the water depth, sediment layer thickness, and changes to bed elevation at different times throughout the barrier lake outburst and subsequent flood processes. Once the barrier lake fills with upstream river inflow, the lake’s water level exceeds the crest of the dam and overtopping begins (Fig. 10a1,  $t = 43$  hr at 17: 00 on 12 October), and the landslide dam body is slightly eroded (Fig. 10c1). The predicted time of first overtopping is half-hour earlier than measured. Five hours after overtopping commences ( $t = 48$  hr at 22: 00 on 12 October), the breaching flow reaches Yebatan and the Jinsha river

468 downstream of the landslide dam resumes flowing with a rather low discharge (Fig. 10a2).  
469 Meanwhile, the overtopping flow gradually erodes the downstream face of the landslide dam  
470 (Fig. 10c2). Subsequently, the overtopping flow rapidly increases (Fig. 8), attaining a value  
471 almost equal to the upstream inflow discharge by  $t = 51$  hr at 01: 00 on 13 October and  
472 peaking at  $t = 55.75$  hr at 05: 45 on 13 October. During this stage, the water depth  
473 downstream of the landslide dam significantly increases, while its upstream counterpart  
474 accordingly decreases (Fig. 10(a3-a4)). Within a further two and half hours, the peak  
475 discharge arrives at Yebatan (Fig. 10a5). Meanwhile the landslide dam is eroded remarkably,  
476 leading to a significant decrease in its crest elevation (Fig. 10(c3-c5)). After time  $t = 64$  hr at  
477 14: 00 on 13 October, a new river channel forms and the Jinsha river resumes base flow, and  
478 is unable to erode further the landslide dam, thus terminating the dam breach process (Fig.  
479 10(a6, b6 and c6)).  
480





482  
 483 **Fig. 10.** “10.10” Landslide-induced barrier lake outburst and the resultant flood: (a1-a6)  
 484 depth of water layer; (b1-b6) water-sediment mixture thickness; and (c1-c6) bed deformation.  
 485 (a1, b1 and c1) Landslide dam is overtopped naturally and dam breach commences. (a2, b2  
 486 and c2) Breaching flow arrives at Yebatan. (a3, b3 and c3) Breaching flow discharge is  
 487 almost equivalent to upstream inflow discharge. (a4, b4 and c4) Breaching flow peaks. (a5,  
 488 b5 and c5) Peak breaching flow arrives at Yebatan. (a6, b6 and c6) Jinsha river resumes its  
 489 base flow and the dam breach process terminates.

490

491

#### 492 4.1.4 Interphase interactions

493 Interphase interactions are evaluated by means of relative velocities. Physically,  
494 interphase interactions quantify momentum and energy transfers between grains and fluid  
495 (Shan and Zhao, 2014), and hence characterize wave hydrodynamics and sediment transport  
496 arising from granular landslides impacting water bodies (Zitti et al., 2016; Miller et al., 2017).  
497 Based on laboratory-scale case studies, Li et al. (2020) revealed that grains play a key role in  
498 driving water movement during the formation of a landslide dam and its associated barrier  
499 lake. However, the subsequent dam breaching process has not yet been fully resolved. Here  
500  $U_{fs}$  and  $V_{fs}$  are defined as longitudinal ( $x$ -axis) and transverse ( $y$ -axis) velocity  
501 differences between the water phase of the water-sediment mixture flow layer and the  
502 sediment phase of a given size Accordingly,  $U_{fs} = u_f - u_{sk}$  and  $V_{fs} = v_f - v_{sk}$ , where  $u_f$   
503 and  $v_f$  are the layer-averaged velocity components of the water phase in the water-sediment  
504 mixture flow layer; and  $u_{sk}$  and  $v_{sk}$  are the size-specific layer-averaged velocity  
505 components of the sediment phase in the water-sediment mixture flow layer. Fig. 11 displays  
506 the velocity differences between the water and size-specific sediment phases in the transverse  
507 direction, and Fig. 12 shows their counterparts in the longitudinal direction. Specifically, Figs.  
508 11 (a1-a3 and b1-b3) and Fig. 12 (a1-a3 and b1-b3) depict the barrier lake formation process,  
509 whereas the remaining subplots refer to the barrier lake outburst and subsequent flood.

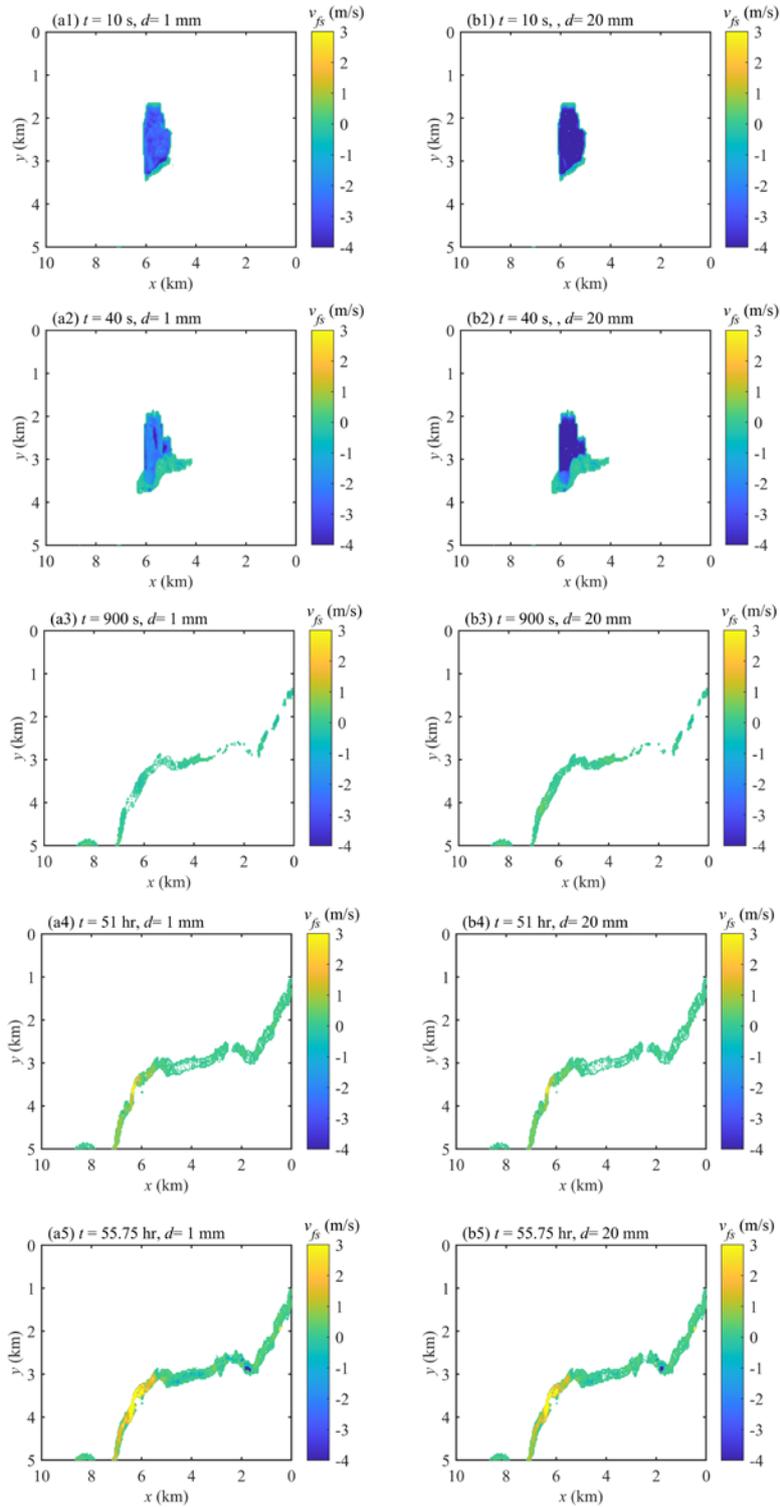
510 During barrier lake formation, as seen in Figs. 11 (a1-a3 and b1-b3) and Figs. 12 (a1-a3  
511 and b1-b3), sediment grains play a primary role in driving water movement, echoing the  
512 finding from a laboratory-scale study by Li et al. (2020). Specifically, the grains generally  
513 have higher speed than the water phase in both the transverse and longitudinal directions.

514 Comparatively, the magnitude of velocity difference in the transverse direction ( $V_{fs}$ ) is  
515 significantly greater than that in the longitudinal direction ( $U_{fs}$ ). Furthermore, coarse grains  
516 move approximately 30% - 40% faster than fine grains in the transverse direction (Fig.  
517 11(a1-a2)), whereas the velocity difference shrinks to 10%-20% in the longitudinal direction  
518 (Fig. 12(a1-a2)). By  $t = 900$  s, as a landslide dam forms due to material deposition, the  
519 velocity differences between the water and sediment phases almost vanish.

520 By contrast, the reverse behaviour occurs during the succeeding processes, as water  
521 governs grain movement. Figs. 11 (a4-a5 and b4-b5) and Figs. 12 (a4-a5 and b4-b5) show  
522 that the water phase generally exhibits higher speed than the grains, and that fine grains move  
523 faster than coarse grains. Although measured data are unavailable to verify quantitatively the  
524 computed results, the present finding is qualitatively consistent with existing experimental  
525 fluvial process observations (Wilcock, 1997) and field data (Drake et al., 1988; Ferguson and  
526 Wathen, 1998; Lenzi, 2004); this further demonstrates the satisfactory performance of the  
527 present model.

528 Figs. 11 and 12 collectively show that water and grain velocities are distinct, thus  
529 characterizing the primary role of grains in driving water movement during landslide dam  
530 and barrier lake formation and the governing role of water in driving grain movement during  
531 barrier lake outburst and the subsequent flood. Overall, these results imply that a double  
532 layer-averaged two-phase flow model is warranted.

533



534

535

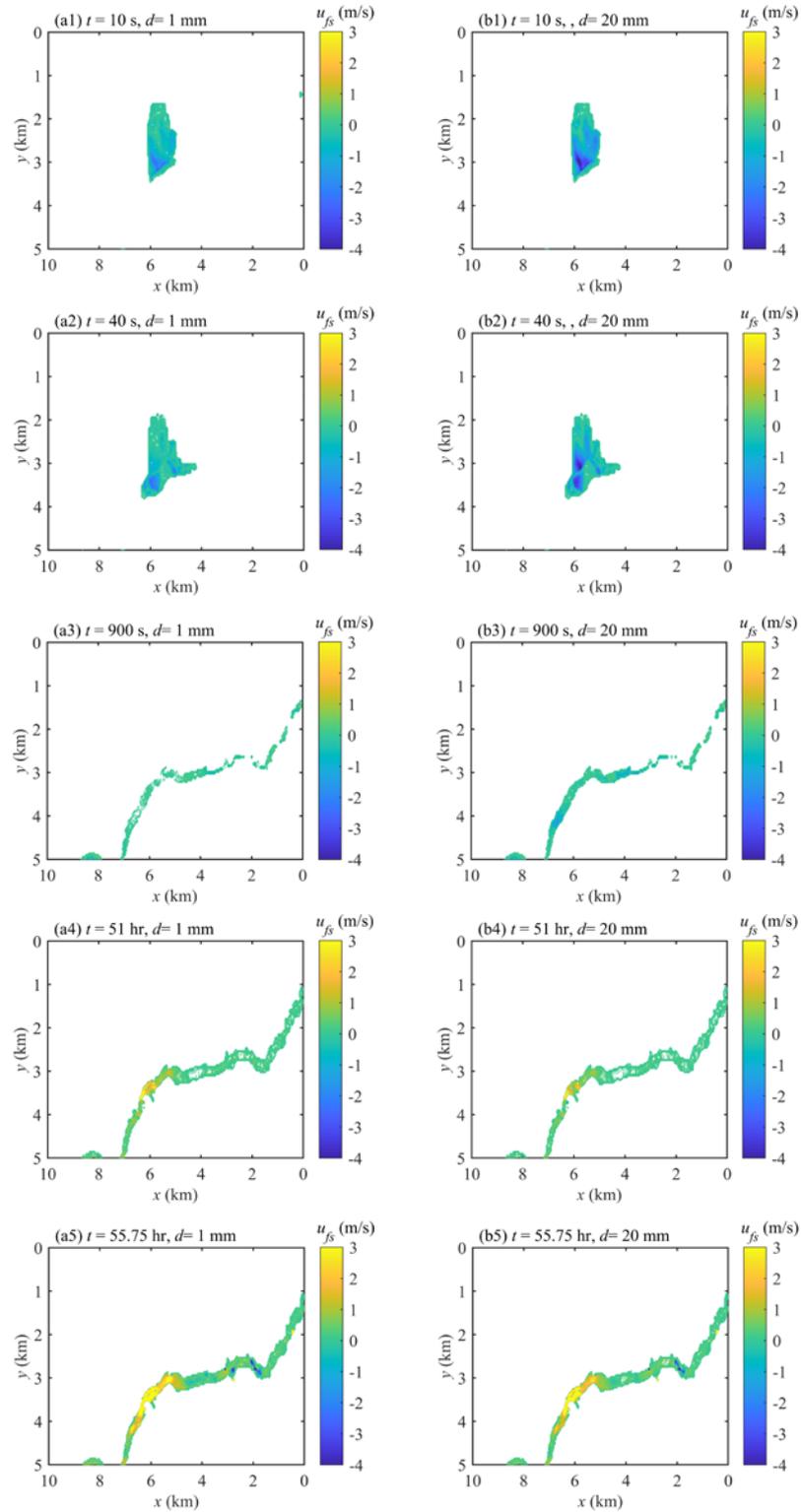
536

537

538

539

**Fig. 11.** Contour plots of velocity difference between water and sediment phases of the water-sediment mixture flow layer in the transverse ( $y$  – axis) direction at different times from 10 s to 55.75 hr after the start of the “10.10” Baige landslide: a1–a5 with  $d = 1$  mm; and b1–b5 with  $d = 20$  mm.



540

541

542

543

544

**Fig. 12.** Contour plots of velocity difference between water and sediment phases of the water-sediment mixture flow layer in the longitudinal ( $x$ – axis) direction at different times from 10 s to 55.75 hr after the start of the “10.10” Baige landslide, a1-a5 with  $d = 1$  mm, and b1-b5 with  $d = 20$  mm.

545

546 *4.1.5. Effects of inflow discharge and landslide volume*

547 Laboratory-scale case studies have found that smaller river flow discharge and larger  
548 landslide volume favour landslide dam and barrier lake formation (Li et al., 2020). Here, two  
549 series of extended numerical cases, designed according to the Phase I “10.10” Baige barrier  
550 lake event, are used to investigate the effects of inflow discharge and landslide volume on a  
551 landslide-induced multi-hazard chain. This is sensible given that potentially unstable rock  
552 mass clusters have been discovered in the source area of the Baige landslides, suggesting  
553 possible future failures with the potential for river damming and flooding (Fan et al. 2020a).

554 *4.1.5.1. Inflow discharge (Series I tests)*

555 Runoff variations in the upper tributaries of the Jinsha River are vulnerable to climate  
556 change (Wu et al., 2020). It is therefore useful to explore the impacts of different upstream  
557 inflow discharges on the landslide-induced multi-hazard chain. Here, the inflow discharge is  
558 tuned by 25% (i.e.,  $1680 \pm 420 \text{ m}^3/\text{s}$ ), and the corresponding results are displayed in Table 3  
559 and Fig. 13. As the inflow discharge increases, the time taken to form a landslide dam  
560 increases and the dam height decreases. This is consistent with the observation by Li et al.  
561 (2020) that small river discharge is conducive to barrier lake formation. In the present  
562 simulations, the time taken to overtop the dam drops substantially from 50.3 hr to 43 hr, and  
563 further to 36.5 hr, as the inflow discharge increases from  $1260 \text{ m}^3/\text{s}$  to  $1680 \text{ m}^3/\text{s}$ , and further  
564 to  $2100 \text{ m}^3/\text{s}$ . From these, corresponding marked reductions in the time available to evacuate  
565 downstream residents may be inferred. Therefore, the risk arising from a barrier lake outburst  
566 would be significantly amplified if the barrier lake was created in the rainy season. The

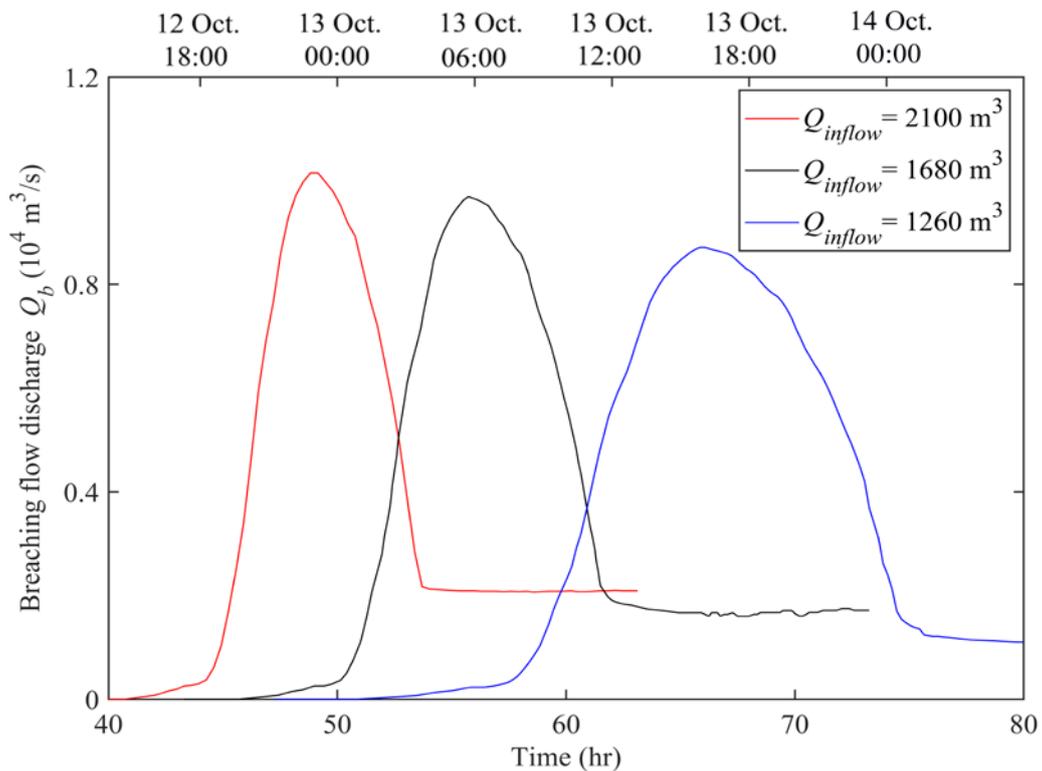
567 simulations also indicate that after the dam overtops naturally, the subsequent peak breach  
 568 flow discharge increases for higher inflow discharge (Table 3 and Fig. 13). Consequently, the  
 569 larger the inflow discharge, the more rapidly the dam is eroded and the shorter the total  
 570 breach duration.

571

572 **Table 3** Predicted effect of inflow discharge on landslide dam formation, overtopping, and  
 573 breaching processes (Series 1 tests)

Results	“10.10” Baige landslide	Series 1-1	Series 1-2
	$Q_{inflow}$	$Q_{inflow}$	$Q_{inflow}$
	(m <sup>3</sup> /s)	(m <sup>3</sup> /s)	(m <sup>3</sup> /s)
	1680	2100	1260
Time to form landslide dam (s)	900	1230	765
Maximum dam height (m)	84.2	76.5	87.2
Time to overtop dam (hr)	43	36.5	50.2
Total breach duration (hr)	21	18.5	23
Peak discharge at dam site (m <sup>3</sup> /s)	9691	10006	8724

574



575

576 **Fig. 13.** Model predictions of breaching flow discharge hydrographs for three different Jinsha  
 577 river inflow discharges.

578

579 *4.1.5.2. Initial landslide volume (Series 2 tests)*

580 For landslide-induced risk assessment, it is of great importance to obtain a measure of the  
 581 landslide magnitude, e.g., through estimating the volume of landslide materials involved  
 582 (Corominas et al., 2014; Fan et al., 2020b). Although the position and movement of a  
 583 landslide can be successfully captured by advanced techniques like remote sensing (Zhang et  
 584 al., 2020), quantification of the initial volume of a landslide nevertheless involves  
 585 considerable uncertainty. With this in mind, Series 2 simulations have been undertaken to  
 586 investigate the sensitivity of the results to the initial landslide volume, which is altered by  
 587  $\pm 50\%$  of the original volume of  $27.5 \times 10^6 \text{ m}^3$ . Table 4 summarizes the results from the Series  
 588 2 simulations, whereas Fig. 14 displays the breaching flow hydrograph under different initial  
 589 landslide volumes. In accordance with Li et al. (2020), a larger initial landslide volume  
 590 favours barrier lake formation as the time to form a landslide dam decreases and the  
 591 maximum dam height increases. Hence, the time taken to overtop the dam increases as the  
 592 initial landslide volume increases. Subsequently, the breaching process is postponed and the  
 593 total breach duration extended. Yet, the peak discharge at the dam site just slightly increases.

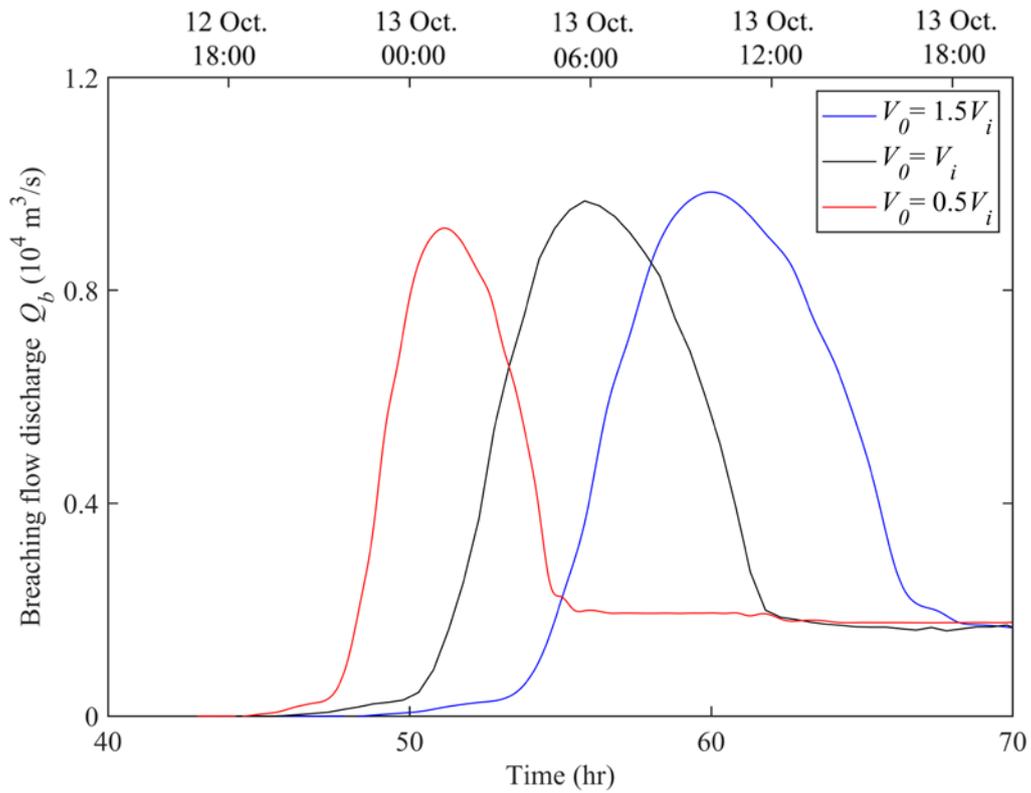
594

595 **Table 4** Predicted effect of inflow landslide volume on landslide dam formation, overtopping,  
 596 and breaching processes (Series 2 tests)

Results	“10.10” Baige landslide	Series 2-1	Series 2-2
	$V_0$	$V_0$	$V_0$

	( $10^6 \text{ m}^3$ )	( $10^6 \text{ m}^3$ )	( $10^6 \text{ m}^3$ )
	27.5	41.25	13.75
Time to form landslide dam (s)	900	700	1356
Maximum dam height (m)	84.2	90.2	74.5
Time to overtop dam (hr)	43	45.3	40.5
Total breach duration (hr)	21	23.7	16.5
Peak discharge at dam site ( $\text{m}^3/\text{s}$ )	9691	9845	9170

597



598

599 **Fig. 14.** Model predictions of breaching flow discharge hydrographs for three different initial  
600 landslide volumes.

601

602 The above analysis clearly demonstrates that whereas small inflow discharge and large  
603 initial landslide volume favour landslide dam and barrier lake formation, they delay the  
604 subsequent barrier lake outburst and the resultant flood downstream. From a physical  
605 perspective, the formation of a landslide dam and its associated barrier lake generally reflects  
606 an aggradation process, whereas the barrier lake outburst and subsequent flood are

607 characterized by an opposing degradation process. The present model properly  
608 accommodates these two distinct but intertwined physical processes, thus facilitating  
609 improved understanding of the complicated physical mechanisms leading to a  
610 landslide-induced barrier lake outburst flood as a multi-hazard causal chain.

611

#### 612 *4.1.6 Sensitivity analysis*

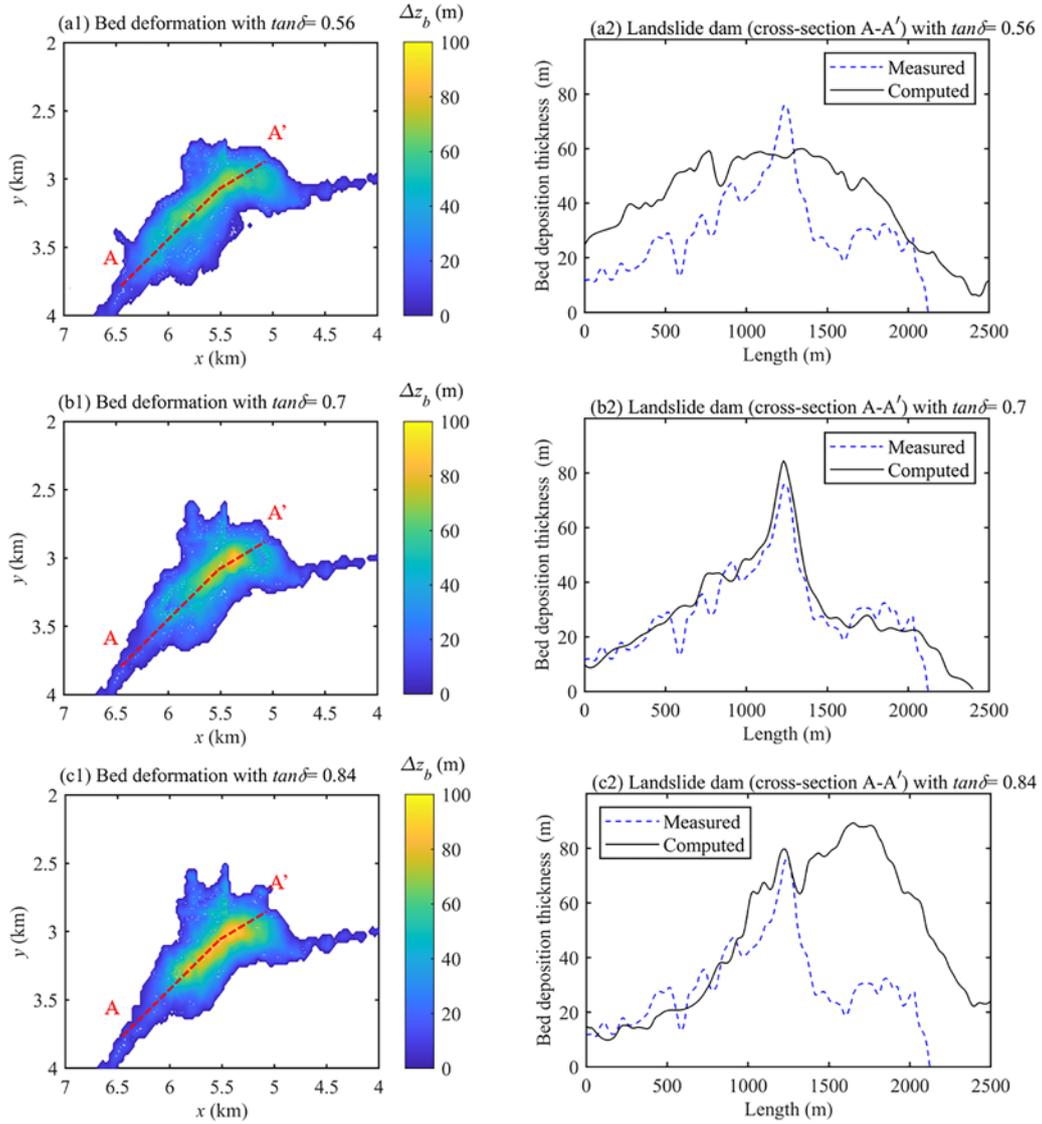
613 Furthermore, numerical tests are conducted to evaluate the sensitivity of the model  
614 results to two model parameters, i.e., bed friction coefficient  $\tan\delta$  and Manning bed  
615 roughness coefficient  $n_b$ , which are separately embedded in the empirical relationships for  
616 the solid and fluid resistance components of the lower sediment-laden flow layer. In addition,  
617 the Manning bed roughness coefficient  $n_b$  is also involved in the bottom resistance of the  
618 clear-water flow layer (Li et al., 2020). Specifically, the Manning bed roughness coefficient  
619  $n_b$  and the bed friction coefficient  $\tan\delta$  are tuned by 25% of the adopted value (i.e.,  
620  $n_b = 0.04 \pm 0.01 \text{ m}^{-1/3} \text{ s}$ ;  $\tan\delta = 0.7 \pm 0.14$ ). In general, the results with tuned parameters in  
621 conventional ranges are qualitatively similar to those shown above when compared with the  
622 measured data.

623 Shown in Figs. 15 and 16 are the computed landslide dam morphology, corresponding to  
624 different values of  $n_b$  and  $\tan\delta$ . Clearly, the computed results are more sensitive to the  
625 value of bed friction coefficient  $\tan\delta$  as compared to that of Manning bed roughness  
626 coefficient  $n_b$ . Most notably, the sensitivity to  $n_b$  is considerably constrained compared  
627 with that to  $\tan\delta$ . Typically, as the value of  $\tan\delta$  increase from 0.56 to 0.84, the value of

628 maximum dam height increases from 59.2 m to 89.5 m. By contrast, in response to the  
629 change of  $n_b$ , their counterparts almost remain unchanged. This difference in behavior  
630 further demonstrates the primary role of grains in driving water movement during landslide  
631 dam and barrier lake formation.

632 Fig. 17(a) shows the impact of  $\tan \delta$  on breaching flow discharge. As shown in Fig. 15,  
633 a larger value of  $\tan \delta$  leads to a higher maximum dam height. Consequently, the time taken  
634 to overtop the dam increases and the subsequent breaching process is postponed. These  
635 simulations also indicate that the peak breaching flow discharge increases for a larger value  
636 of  $\tan \delta$ . Specifically, with  $\tan \delta = 0.56$ , the peak discharge is 8732 m<sup>3</sup>/s occurring at  $t =$   
637 49.6 hr, whereas with  $\tan \delta = 0.84$ , the peak discharge increases to 10170 m<sup>3</sup>/s, postponing to  
638  $t = 61.88$  hr. Fig. 17(b) illustrates the effect of  $n_b$ . Despite its marginal impact on landslide  
639 dam morphology, a larger value of  $n_b$  leads to a larger peak discharge and an earlier  
640 occurrence. Specifically, with  $n_b$  increasing from 0.03 to 0.05 m<sup>-1/3</sup> s, the peak discharge  
641 increases from 8700 m<sup>3</sup>/s to 10400 m<sup>3</sup>/s and its timing is advanced from  $t = 61.3$  hr to  $t =$   
642 51.6 hr.

643



644

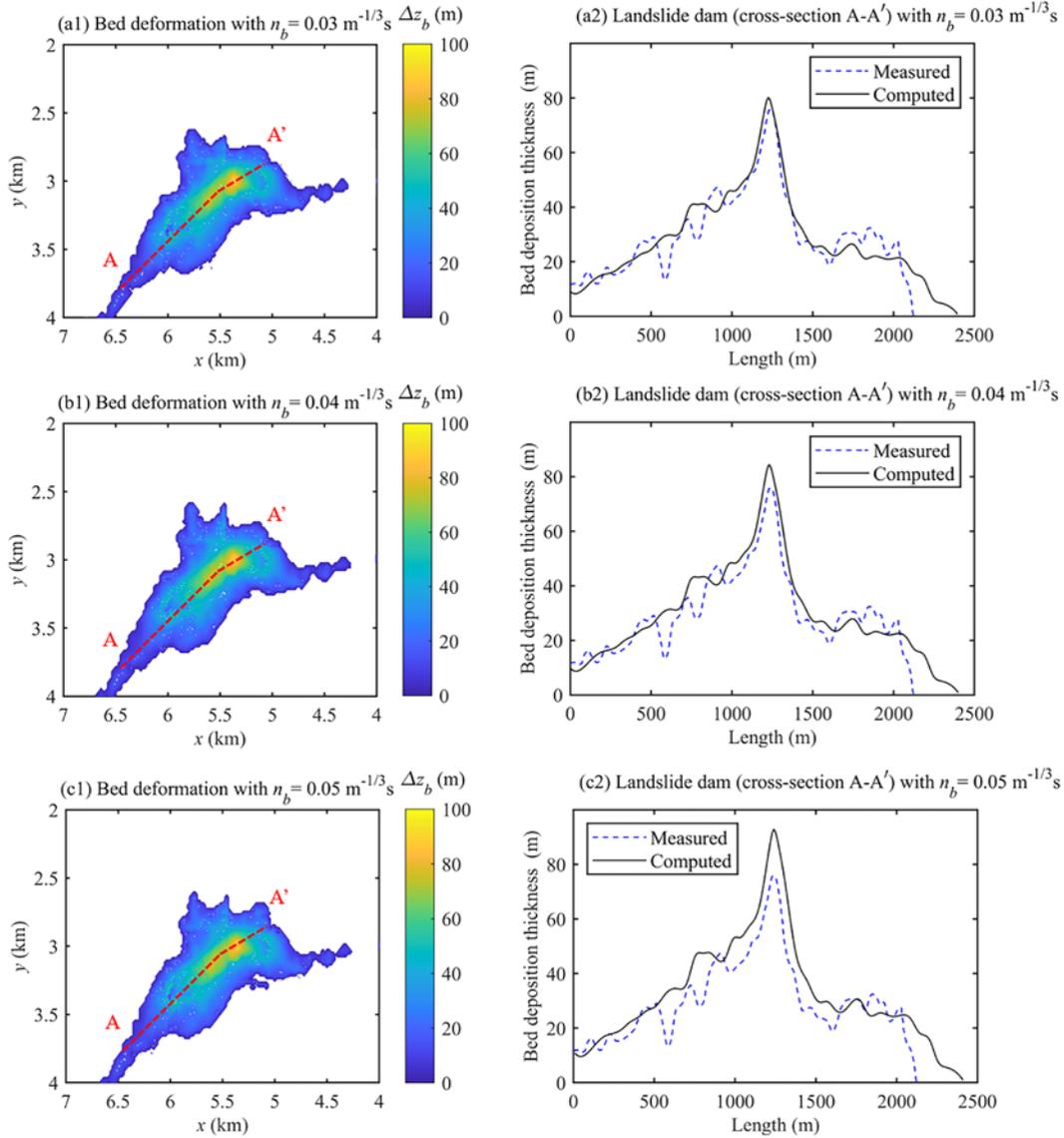
645 **Fig. 15.** “10.10” Baige landslide dam morphology assuming different bed friction coefficient

646  $\tan \delta$  (a1-a3) bed deformation at  $t = 900$  s predicted by present model; and (b1-b3)

647 cross-section profile of landslide dam in the original river stream-wise direction (A-A’):

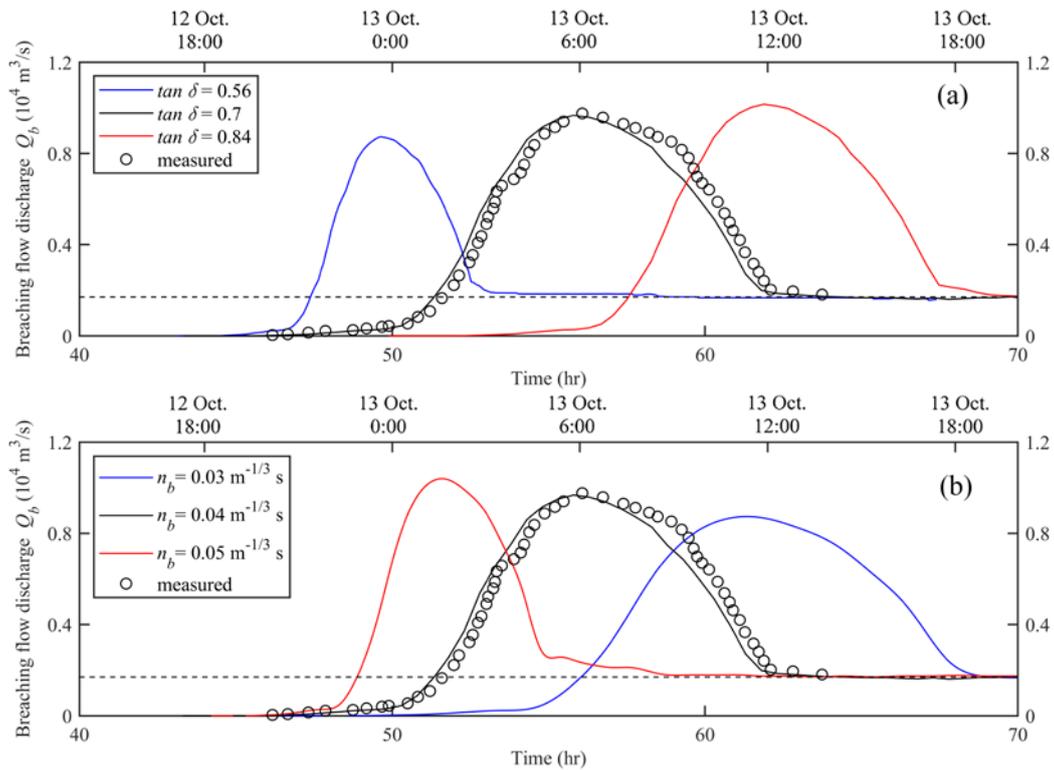
648 model prediction (solid line) and measured data from Fan et al. (2020a) (dashed line).

649



650  
 651  
 652  
 653  
 654  
 655

**Fig. 16.** “10.10” Baige landslide dam morphology assuming different Manning roughness coefficient  $n_b$  (a1-a3) bed deformation at  $t = 900$  s predicted by present model; and (b1-b3) cross-section profile of landslide dam in the original river stream-wise direction (A-A’): model prediction (solid line) and measured data from Fan et al. (2020a) (dashed line).



656  
 657 **Fig. 17.** Model predictions (solid lines) of breaching flow discharge hydrographs assuming (a)  
 658 different bed friction coefficient  $\tan \delta$  ; and (b) different Manning roughness coefficient  $n_b$   
 659 and measured data (open circles) from Cai et al. (2019).

660

661 *4.2. Phase II: “11.03” Baige barrier lake event*

662 We now revisit the Phase II “11.03” Baige barrier lake event. This second landslide dam  
 663 formed on residual material from the first landslide dam, causing the barrier lake to triple in  
 664 volume. To reduce downstream flood risk due to barrier lake outburst, an artificial flood  
 665 channel was urgently constructed, with a total of 85,000 m<sup>3</sup> of soil and rock excavated (Cai et  
 666 al., 2019).

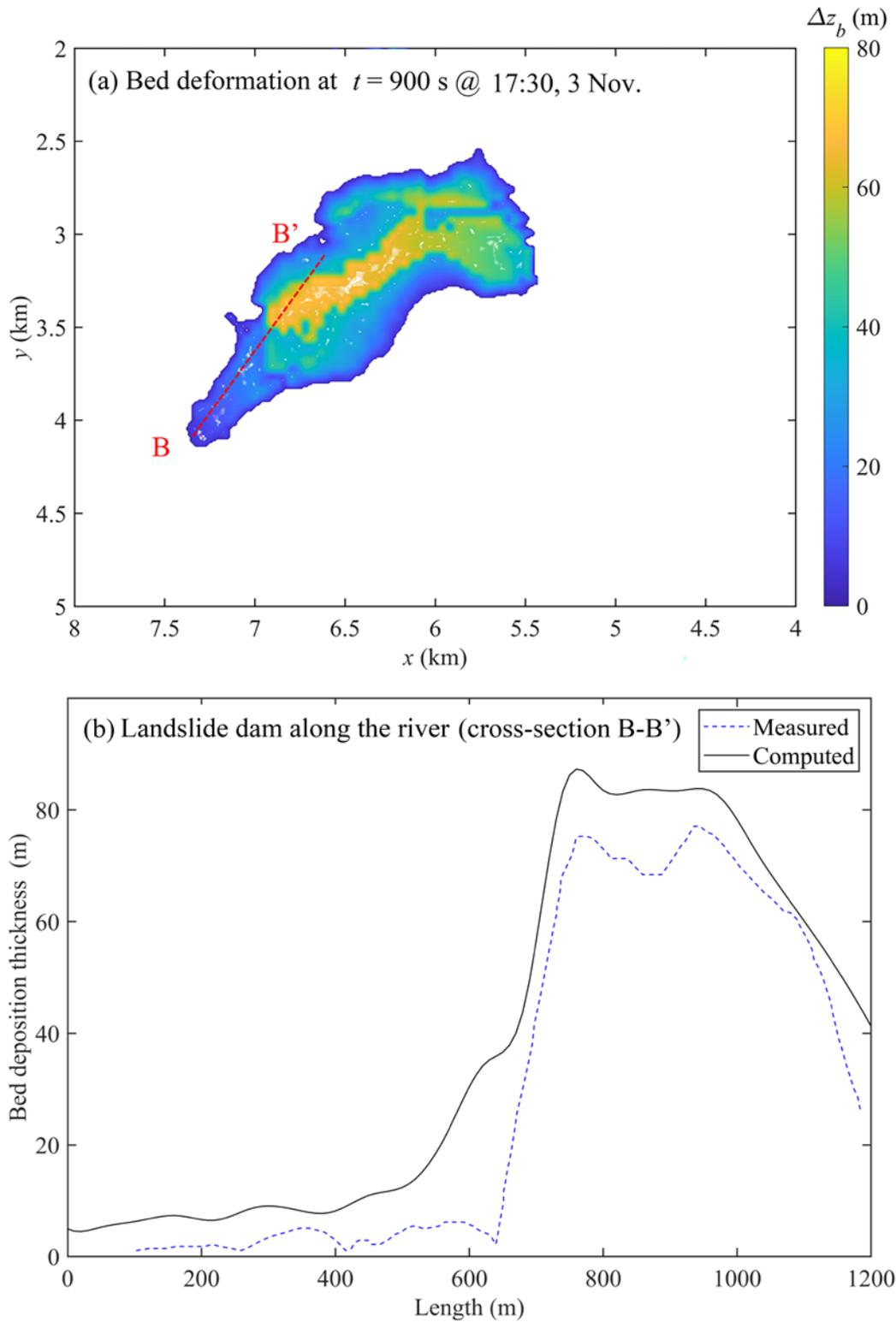
667 Fig. 18(a) shows the landslide dam morphology as represented by the bed deformation at  
 668  $t = 900$  s (noting that  $t = 0$  s is now set to the start of the “11.03” landslide). Similar to its  
 669 predecessor due to the first landslide (Fig. 6), the height of the second landslide dam is higher  
 670 on the upstream relative to the downstream side with respect to the Jinsha river. Fig. 18(b)

671 presents predicted and observed cross-section profiles of the landslide dam taken in a  
672 longitudinal direction approximately along the river (B-B', see Fig. 18a). The  $L^1$  norm for  
673 bed deposition thickness  $L_{bd}^1 = 22.38\%$ . The present model predictions are in reasonable  
674 agreement with observed data, except for a general overprediction of the bed deposition layer  
675 thickness.

676 Fig. 19 presents discharge hydrographs and water level time series at the landslide dam  
677 site and the Yebatan station. Although quantitative differences between the model predictions  
678 and field observations are inevitable, the computed discharges and water levels are reasonably  
679 consistent with those reported by Cai et al. (2019). The model predicts a peak breach  
680 discharge of 32,787 m<sup>3</sup>/s, occurring at 17:28 on 13 November, a difference in maximum  
681 discharge of 3.2% and occurrence time of < 1 hr compared to the observed data. The  
682 predicted water level time history at the dam site is remarkably close to the measured series at  
683 Boluo station, 20 km upstream of the dam, until the barrier lake outburst occurs, after which  
684 the predicted result at the dam site is appreciably lower than that measured at Boluo. This  
685 behaviour arises because the water level at the Baige landslide dam site was almost  
686 equivalent to that at Boluo while the barrier lake is full, but was appreciably lower than that  
687 at Boluo after the barrier lake outburst occurred. Fig. 19(b) compares predicted and measured  
688 discharge hydrographs at Yebatan, the downstream station, along with computed sediment  
689 volume output time series. Similar to the results obtained for Phase II (Fig. 8), the peak  
690 discharge attenuates as the wave travels along the river. At Yebatan, the peak discharge is  
691 predicted to occur at 19:10 on 13 November, with a value of 26,817 m<sup>3</sup>/s, whereas the  
692 observed maximum discharge is 28,057 m<sup>3</sup>/s at 19:50 on 13 November. Subsequently, the

693 Jinsha river gradually reverts to base flow. The corresponding  $L^1$  norms for breaching flow  
694 discharge hydrography  $L_{Q_b}^1$  and flow discharge hydrograph at Yebatan gauging station  $L_Q^1$   
695 are 23.22% and 25.47% respectively. At the end of “11.03” Baige barrier lake event,  
696 approximately  $5.96 \times 10^6 \text{ m}^3$  of sediments have been carried away through Yebatan.  
697 Consequently, an addition  $6.04 \times 10^6 \text{ m}^3$  of sediment [=  $12 \times 10^6 \text{ m}^3$  (total volume of “11.03”  
698 Baige landslide) –  $5.96 \times 10^6 \text{ m}^3$  (sediment volume output)] has been deposited in the river  
699 channel between dam site and Yebatan.

700



701

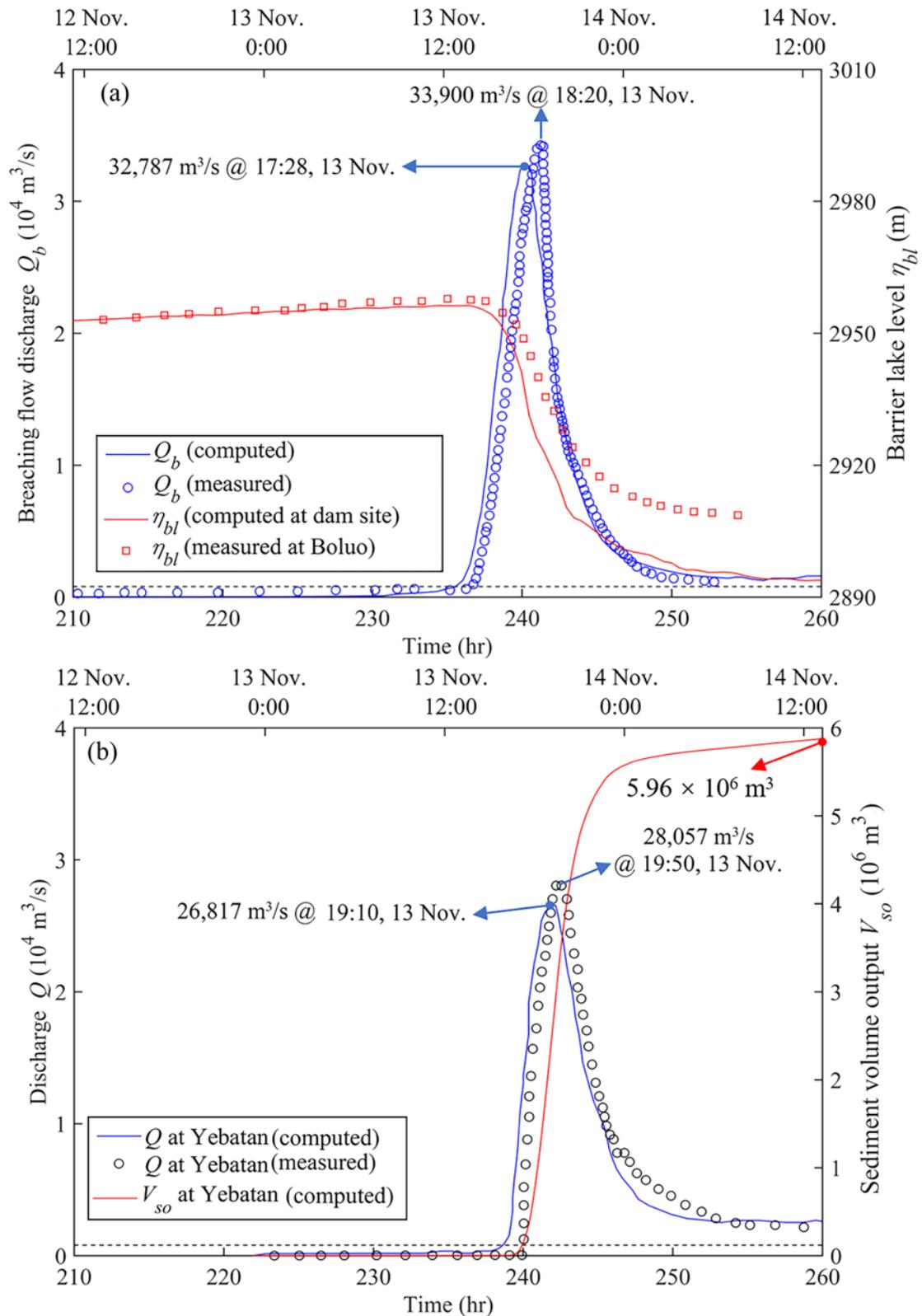
702

703

704

705

**Fig. 18.** “11.03” Baige landslide dam geometry: (a) predicted bed deformation contours at  $t = 900$  s; and (b) predicted (solid line) and measured (dashed line, Fan et al. 2020a) cross-sectional profiles of the landslide dam in a longitudinal direction along the river (B-B’).

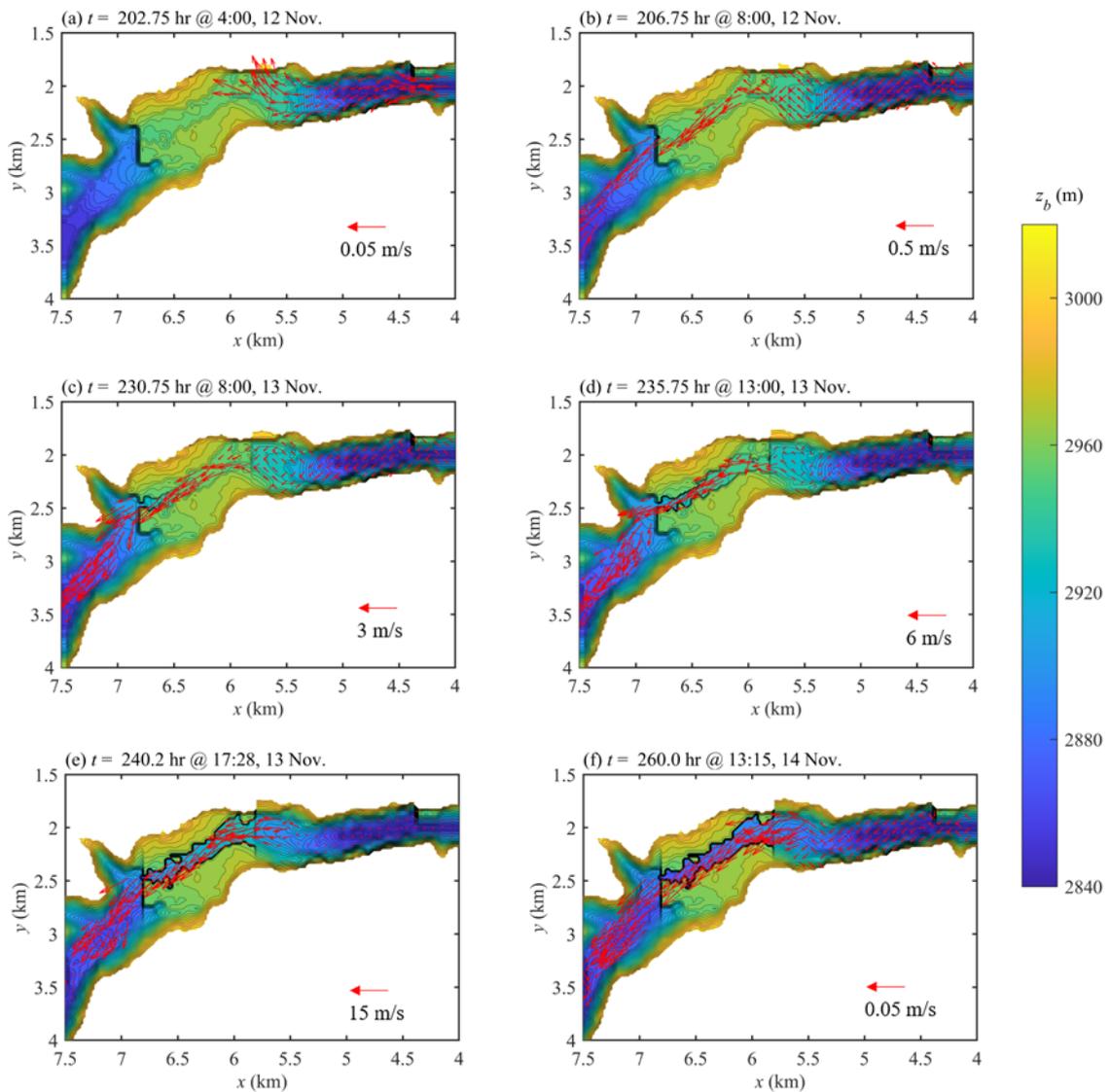


706  
707  
708  
709  
710

**Fig. 19.** (a) Breaching flow discharge hydrograph and water level time series at the “11.03” Baige landslide dam site; (b) flow discharge hydrograph and sediment volume output series at Yebatan (the downstream station): model predictions (solid lines) and measured data (open circles).

711  
712  
713  
714  
715  
716  
717  
718  
719  
720  
721  
722  
723  
724  
725  
726  
727  
728  
729  
730

Fig. 20 presents contour plots of the evolution of the dam breach with instantaneous flow velocity vectors superimposed. At  $t = 202.75$  hr at 4:00 on 12 November (Fig. 20a), the water level of the barrier lake rises above the bed level of the artificial flood channel and overtopping commences. The overtopping flow then traverses the dam crest as an almost uniform sheet. The breach channel hardly widens, while the main dam body slightly erodes (Fig. 20b). During the next stage, breach channel enlarges slowly over a relatively long period (about 24 hrs). Meanwhile, the steepest section of the downstream face of the dam experiences significant erosion (Fig. 20c), which causes the flow velocity to increase locally. The resultant rapid flow in this steep section entrains further sediment and intensive scouring rapidly propagates backward toward the upstream area (Fig. 20d). Such headward erosion raises the breaching flow discharge (Fig. 19), leading to progressive vertical and horizontal enlargement of the breach channel (Fig. 20d and e). In general, breach deepening is associated with steepening of the sidewalls that may collapse once a critical failure angle is exceeded, leading to breach widening. In addition, the river channel downstream of the landslide dam accretes sediment scoured from the dam. The model indicates that high flow speeds, up to 15 m/s occur as the breaching flow discharge increases. Accordingly, both flow speed and bed erosion decrease as the barrier lake water level decreases and the river flow returns to base flow (Fig. 20f).



731

732 **Fig. 20.** “11.03” Baige landslide dam breach evolution depicted as bed deformation contours

733 and superimposed flow velocity vectors at post-landslide times,  $t =$ : (a) 202.75 hr; (b) 206.75

734 hr; (c) 230.75 hr; (d) 235.75 hr; (e) 240.2 hr; and (f) 260.0 hr.

735

736 A further scenario is now considered for the case of the second landslide dam in the

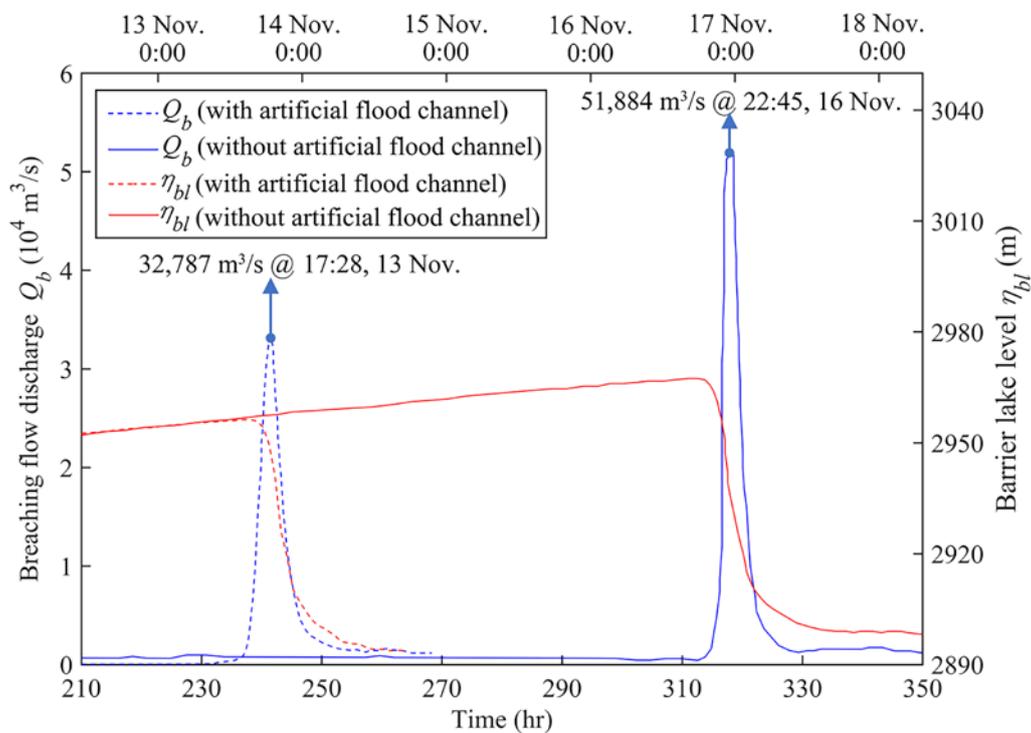
737 absence of an artificial flood channel. The computation automatically terminated once the

738 river flow returned to base flow. Fig. 21 displays the predicted breach flow discharge

739 hydrograph and barrier lake level time series. In the absence of an artificial flood channel, the

740 breaching process is significantly delayed, the peak discharge much larger, and the barrier  
 741 lake level raised. This finding is qualitatively consistent with experimental observations from  
 742 another landslide dam failure (Cao et al., 2011a). For a constant inflow discharge of 800 m<sup>3</sup>/s,  
 743 the model estimates that 3 more days will be taken to fill the barrier lake and overtop the  
 744 landslide dam (than for the case with the artificial channel present). In the absence of the  
 745 channel, the model predicts that the peak breaching flow discharge would reach 51,884 m<sup>3</sup>/s  
 746 (an increase of 58.2%) at 22:45 on 16 November, and the maximum water level of the barrier  
 747 lake would attain 2967.5 m (an increase of 11.2 m). As would be expected, the model predicts  
 748 that construction of an artificial flood channel would significantly alleviate downstream flood  
 749 risk.

750



751

752 **Fig. 21.** Model predictions of breaching flow discharge hydrographs (blue) and barrier lake  
 753 level time series (red): scenario with artificial flood channel (dashed lines); and scenario  
 754 without an artificial flood channel (solid lines).

755

756 Table 5 summarizes the  $L^1$  values of the model prediction for Baige barrier lake events,  
757 which quantitatively demonstrate that the computed results are in good agreement with the  
758 measured data. Furthermore, it shows that the error of the numerical solution accumulates  
759 and propagates within Phase I, from landslide dam and barrier lake formation, through to  
760 barrier lake outburst and downstream flooding, then extending to Phase II, in which a further  
761 propagation and accumulation can be observed.

762

763 **Table 5** Summary of  $L^1$  norms of model prediction for Baige barrier lake events

$L^1$	Phase I	Phase II
Landslide dam morphology $L_{bd}^1$	12.45%	22.38%
Breaching flow discharge hydrograph $L_{Q_b}^1$	15.31%	23.22%
Flow discharge hydrograph at Yebatan $L_Q^1$	15.85%	25.47%

764

## 765 **5. Conclusions**

766 The Baige barrier lake events of 2018 offers unique insight into landslide-induced  
767 multi-hazard chains that could produce catastrophic disasters extending far beyond the source  
768 zone. Based on a recent 2D double layer-averaged two-phase flow model, we reconstruct the  
769 whole process of the Baige barrier lake outburst flood within a single model run,  
770 encompassing landslide-generated waves, landslide dam and barrier lake formation, the  
771 barrier lake outburst, and the subsequent downstream flood. In terms of landslide-generated

772 waves, landslide dam morphology, stage time series and discharge hydrographs at the dam  
773 site and a downstream gauging station, the present model solutions are in good agreement  
774 with field observations. Construction of an artificial flood channel at the dam crest is  
775 demonstrated to be an effective mitigation strategy for downstream flood risk arising from a  
776 barrier lake outburst. The present work reveals the primary role of grains in landslide dam  
777 formation and also the dominant role of water in the barrier lake outburst and the resultant  
778 flood. Moreover, whilst small river flow discharge and large initial landslide volume favour  
779 landslide dam and barrier lake formation, they delay the occurrence time of the barrier lake  
780 outburst and its subsequent flood.

781 The present modelling framework offers considerable promise for assessing  
782 landslide-induced multi-hazard chains, and informing mitigation and adaptation strategies.  
783 Such an approach is particularly timely, given the increased instability of high mountain  
784 slopes and the accelerating trends in extreme precipitation amount, intensity and frequency of  
785 occurrence due to climate change, which are likely to trigger increasing numbers of  
786 landslides in the future. The modelling framework would achieve high computational  
787 efficiency by implementation of unstructured grids, parallel architecture and adaptive  
788 local-time-step techniques, thus supporting timely decision making in emergency response  
789 operation. Inevitably, the model incurs uncertainty arising from incomplete knowledge of the  
790 estimates of mass exchanges between the landslide and the bed, and interface and bed  
791 resistances. Therefore, systematic fundamental investigations are therefore recommended into  
792 the mechanisms associated with these exchanges and resistances.

793

794 **Acknowledgements**

795 This work was funded by Natural Science Foundation of China under Grant No. 11672212.

796

797 **References**

798 Abadie, S., Harris, J.C., Grilli, S.T., Fabre, R., 2012. Numerical modeling of tsunami waves  
799 generated by the flank collapse of the Cumbre Vieja Volcano (La Palma, Canary Islands):  
800 Tsunami source and near field effects. *J. Geophys. Res.-Oceans* 117, C05030.  
801 <http://dx.doi.org/10.1029/2011JC007646>.

802 ASCE/EWRI Task Committee on Dam/Levee Breaching, 2011. Earthen embankment  
803 breaching. *J. Hydraul. Eng.* 137(12), 1549-1564.  
804 [https://doi.org/10.1061/\(ASCE\)HY.1943-7900.0000498](https://doi.org/10.1061/(ASCE)HY.1943-7900.0000498).

805 Bandara, S., Soga, K., 2015. Coupling of soil deformation and pore fluid flow using material  
806 point method. *Comput. Geotech.* 63, 199-214.  
807 <https://doi.org/10.1016/j.compgeo.2014.09.009>.

808 Cai, Y., Luan, Y., Yang, Q., Xu, F., Zhang, S., Shi, Y., Yidu, L., 2019. Study on structural  
809 morphology and dam-break characteristics of Baige barrier dam on Jinsha River.  
810 *Yangtze River* 50(3), 15-22 (in Chinese).

811 Cao, Z., Pender, G., Wallis, S., Carling, P., 2004. Computational dam-break hydraulics over  
812 erodible sediment bed. *J. Hydraul. Eng.* 130(7), 689-703.  
813 [http://dx.doi.org/10.1061/\(ASCE\)0733-9429\(2004\)130:7\(689\)](http://dx.doi.org/10.1061/(ASCE)0733-9429(2004)130:7(689)).

814 Cao, Z., Yue, Z., Pender, G., 2011a. Landslide dam failure and flood hydraulics. Part I:  
815 experimental investigation. *Nat. Hazards* 59(2), 1003-1019.  
816 <https://doi.org/10.1007/s11069-011-9814-8>.

817 Cao, Z., Yue, Z., Pender, G., 2011b. Landslide dam failure and flood hydraulics. Part II:  
818 coupled mathematical modelling. *Nat. Hazards* 59(2), 1021-1045.  
819 <https://doi.org/10.1007/s11069-011-9815-7>.

820 Cao, Z., Yue, Z., Pender, G., 2011c. Flood hydraulics due to cascade landslide dam failure. *J.*  
821 *Flood Risk Manag.* 4(2), 104-114. <https://doi.org/10.1111/j.1753-318X.2011.01098.x>.

822 Cao, Z., Xia, C., Pender, G., Liu, Q., 2017. Shallow water hydro-sediment-morphodynamic  
823 equations for fluvial processes. *J. Hydraul. Eng.* 143(5), 02517001.  
824 [http://dx.doi.org/10.1061/\(ASCE\)HY.1943-7900.0001281](http://dx.doi.org/10.1061/(ASCE)HY.1943-7900.0001281).

825 Carpignano, A., Golia, E., Di Mauro, C., Bouchon, S., Nordvik, J. P., 2009. A methodological  
826 approach for the definition of multi-risk maps at regional level: first application. *J. Risk*  
827 *Res.* 12(3-4), 513-534. <https://doi.org/10.1080/13669870903050269>.

828 Carrivick, J. L., 2010. Dam break-Outburst flood propagation and transient hydraulics: A  
829 geosciences perspective. *J. Hydro.* 380(3-4), 338-355.  
830 <https://doi.org/10.1016/j.jhydrol.2009.11.009>.

831 Chang, D. S., Zhang, L. M., 2010. Simulation of the erosion process of landslide dams due to  
832 overtopping considering variations in soil erodibility along depth. *Nat. Hazard Earth Sys.*  
833 10(4), 933. <https://doi.org/10.5194/nhess-10-933-2010>.

834 Chen, C., Zhang, L., Xiao, T., He, J., 2020. Barrier lake bursting and flood routing in the  
835 Yarlung Tsangpo Grand Canyon in October 2018. *J. Hydro.* 583, 124603.  
836 <https://doi.org/10.1016/j.jhydrol.2020.124603>.

837 Corominas, J., van Westen, C., Frattini, P., Cascini, L., Malet, J.P., Fotopoulou, S., Catani, F.,  
838 Van Den Eeckhaut, M., Mavrouli, O., Agliardi, F. and Pitilakis, K., 2014.  
839 Recommendations for the quantitative analysis of landslide risk. *Bull. Eng. Geo. Environ.*  
840 73(2), 209-263. <https://doi.org/10.1007/s10064-013-0538-8>.

841 Costa, J. E., Schuster, R. L., 1988. The formation and failure of natural dams. *Geol. Soc. Am.*  
842 *Bull.* 100(7), 1054-1068.  
843 [https://doi.org/10.1130/0016-7606\(1988\)100<1054:TFAFON>2.3.CO;2](https://doi.org/10.1130/0016-7606(1988)100<1054:TFAFON>2.3.CO;2).

844 Cui, P., Zhou, G.G.D., Zhu, X.H., Zhang, J.Q., 2013. Scale amplification of natural debris  
845 flows caused by cascading landslide dam failures. *Geomorphology* 182, 173–189.  
846 <https://doi.org/10.1016/j.geomorph.2012.11.009>.

847 Dai, F. C., Lee, C. F., Deng, J. H., Tham, L. G., 2005. The 1786 earthquake-triggered  
848 landslide dam and subsequent dam-break flood on the Dadu River, southwestern China.  
849 *Geomorphology* 65(3-4), 205-221. <https://doi.org/10.1016/j.geomorph.2004.08.011>.

850 Davies, T. R., Manville, V., Kunz, M., Donadini, L., 2007. Modeling landslide dam break  
851 flood magnitudes: case study. *J. Hydraul. Eng.* 133(7), 713–720.  
852 [https://doi.org/10.1061/\(ASCE\)0733-9429\(2007\)133:7\(713\)](https://doi.org/10.1061/(ASCE)0733-9429(2007)133:7(713)).

853 Delaney, K. B., Evans, S. G., 2015. The 2000 Yigong landslide (Tibetan Plateau),  
854 rockslide-dammed lake and outburst flood: review, remote sensing analysis, and process  
855 modelling. *Geomorphology* 246, 377-393.  
856 <https://doi.org/10.1016/j.geomorph.2015.06.020>.

857 Donat, M. G., Alexander, L. V., Yang, H., Durre, I., Vose, R., Dunn, R. J. H., ... & Hewitson,  
858 B. (2013). Updated analyses of temperature and precipitation extreme indices since the  
859 beginning of the twentieth century: The HadEX2 dataset. *J. Geophys. Res.-*  
860 *Atmospheres* 118(5), 2098-2118. <https://doi.org/10.1002/jgrd.50150>.

861 Drake, T.G., Shreve, R.L., Dietrich, W.E., Whiting, P.J., Leopold, L.B., 1988. Bedload  
862 transport of fine gravel observed by motion-picture photography. *J. Fluid Mech.* 192,  
863 193-217. <https://dx.doi.org/10.1017/S0022112088001831>.

864 Ermini, L., Casagli, N., 2003. Prediction of the behaviour of landslide dams using a  
865 geomorphological dimensionless index. *Earth Surf. Proc. Land.* 28(1), 31-47.  
866 <https://doi.org/10.1002/esp.424>.

867 Faeh, R., 2007. Numerical modeling of breach erosion of river embankments. *J. Hydraul. Eng.*  
868 133(9), 1000-1009. [https://doi.org/10.1061/\(ASCE\)0733-9429\(2007\)133:9\(1000\)](https://doi.org/10.1061/(ASCE)0733-9429(2007)133:9(1000)).

869 Fan, X., Scaringi, G., Korup, O., West, A. J. et al., 2019a. Earthquake-induced chains of  
870 geologic hazards: Patterns, mechanisms, and impacts. *Rev. Geophys.* 57(2), 421-503.  
871 <https://doi.org/10.1029/2018RG000626>.

872 Fan, X., Xu, Q., Alonso-Rodriguez, A. et al., 2019b. Successive landsliding and damming of  
873 the Jinsha River in eastern Tibet, China: prime investigation, early warning, and  
874 emergency response. *Landslides* 16(5), 1003-1020.  
875 <https://doi.org/10.1007/s10346-019-01159-x>.

876 Fan, X., Yang, F., Subramanian, S. S. et al., 2020a. Prediction of a multi-hazard chain by an  
877 integrated numerical simulation approach: the Baige landslide, Jinsha River, China.  
878 *Landslides* 17(1), 147-164. <https://doi.org/10.1007/s10346-019-01313-5>.

879 Fan, X., Dufresne, A., Subramanian, S. S., Strom, A. et al. 2020b. The formation and impact  
880 of landslide dams—State of the art. *Earth-Science Reviews*, 103116.  
881 <https://doi.org/10.1016/j.earscirev.2020.103116>.

882 Fread, D. L., 1988. BREACH: an erosion model for earthen dam failure. U.S. Department of  
883 Commerce, National Oceanic and Atmospheric Administration, National Weather

884 Service, Office of Hydrology, Silver Spring, USA.

885 Ferguson, R. I., Wathen, S. J., 1998. Tracer-pebble movement along a concave river profile:  
886 virtual velocity in relation to grain size and shear stress. *Water Resour. Res.* 34 (8),  
887 2031–2038. <http://dx.doi.org/10.1029/98WR01283>.

888 Hu, Y., Yu, Z., Zhou, J., 2020. Numerical simulation of landslide-generated waves during the  
889 11 October 2018 Baige landslide at the Jinsha River. *Landslides*, 17, 2317–2328.  
890 <https://doi.org/10.1007/s10346-020-01382-x>.

891 Huang, W., Cao, Z., Yue, Z., Pender, G., Zhou, J. 2012. Coupled modelling of flood due to  
892 natural landslide dam breach. *Proc. ICE Water Manag.* 165, 525-542.  
893 <https://doi.org/10.1680/wama.12.00017>.

894 Lee, C. F., Dai, F. C., 2011. The 1786 Dadu River Landslide Dam, Sichuan, China, in: Evans,  
895 S., Hermanns, R., Strom, A., Scarascia-Mugnozza, G. (Eds.), *Natural and Artificial*  
896 *Rockslide Dams*. Springer, Berlin, Heidelberg, pp. 369-388.  
897 [https://doi.org/10.1007/978-3-642-04764-0\\_13](https://doi.org/10.1007/978-3-642-04764-0_13)

898 Lenzi, M.A., 2004. Displacement and transport of marked pebbles, cobbles and boulders  
899 during floods in a steep mountain stream. *Hydrol. Process* 18 (10), 1899– 1914.  
900 <http://dx.doi.org/10.1002/hyp.1456>.

901 Leonardi, A., Wittel, F. K., Mendoza, M., Vetter, R., Herrmann, H. J., 2016.  
902 Particle-fluid-structure interaction for debris flow impact on flexible barriers.  
903 *Comput-aided Civ. Inf. Eng.* 31(5), 323-333. <https://doi.org/10.1111/mice.12165>.

904 Li, J., Cao, Z., Pender, G., Liu, Q., 2013. A double layer-averaged model for dam-break flows  
905 over mobile bed. *J. Hydraul. Res.* 51(5), 518-534.  
906 <https://doi.org/10.1080/00221686.2013.812047>.

907 Li, J., Cao, Z., Liu, Q., 2019. Waves and sediment transport due to granular landslides  
908 impacting reservoirs. *Water Resour. Res.* 55(1), 495-518.  
909 <https://doi.org/10.1029/2018WR023191>.

910 Li, J., Cao, Z., Cui, Y., Borthwick, A., 2020. Barrier lake formation due to landslide  
911 impacting a river: A numerical study using a double layer-averaged two-phase flow  
912 model. *Appl. Math. Model.* 80, 574-601. <https://doi.org/10.1016/j.apm.2019.11.031>.

913 Liang, Q., Borthwick, A., 2009. Adaptive quadtree simulation of shallow flows with wet–dry  
914 fronts over complex topography. *Comput. Fluids* 38(2), 221-234.

915 <http://dx.doi.org/10.1016/j.compfluid.2008.02.008>.

916 Liu, W., He, S., 2016. A two-layer model for simulating landslide dam over mobile river beds.  
917 *Landslides* 13(3), 565-576. <https://doi.org/10.1007/s10346-015-0585-2>.

918 Liu, W., He, S., 2018. Dynamic simulation of a mountain disaster chain: landslides, barrier  
919 lakes, and outburst floods. *Nat. Hazards* 90(2), 757-775.  
920 <https://doi.org/10.1007/s11069-017-3073-2>.

921 Miller, G. S., Andy Take, W., Mulligan, R. P., McDougall, S., 2017. Tsunamis generated by  
922 long and thin granular landslides in a large flume. *J. Geophys. Res.- Oceans* 122(1),  
923 653-668. <http://dx.doi.org/10.1002/2016JC012177>.

924 Morris, J. F., 2009. A review of microstructure in concentrated suspensions and its  
925 implications for rheology and bulk flow. *Rheol. Acta* 48(8), 909-923.  
926 <https://doi.org/10.1007/s00397-009-0352-1>.

927 Morris, M. W., Kortenhaus, A., Visser, P. J., 2009. Modelling breach initiation and growth.  
928 FLOODsite Report T06-08-02, FLOODsite Project, HR Wallingford, UK.

929 O'Brien, J. S., Julien, P. Y., Fullerton, W. T., 1993. Two-dimensional water flood and mudflow  
930 simulation. *J. Hydraul. Eng.* 119(2), 244-261.  
931 [https://doi.org/10.1061/\(ASCE\)0733-9429\(1993\)119:2\(244\)](https://doi.org/10.1061/(ASCE)0733-9429(1993)119:2(244)).

932 Peng, M., Zhang, L. M., 2012. Breaching parameters of landslide dams. *Landslides* 9(1),  
933 13-31. <https://doi.org/10.1007/s10346-011-0271-y>.

934 Pudasaini, S. P., 2012. A general two-phase debris flow model. *J. Geophys. Res.- Earth Surf.*  
935 117(F3). <https://doi.org/10.1029/2011JF002186>.

936 Reeks, M. W., Hall, D., 2001. Kinetic models for particle resuspension in turbulent flows:  
937 theory and measurement. *J. Aerosol Sci.* 32(1), 1-31.  
938 [https://doi.org/10.1016/S0021-8502\(00\)00063-X](https://doi.org/10.1016/S0021-8502(00)00063-X).

939 Shan, T., Zhao, J., 2014. A coupled CFD-DEM analysis of granular flow impacting on a  
940 water reservoir. *Acta Mech.* 225(8), 2449-2470.  
941 <http://dx.doi.org/10.1007/s00707-014-1119-z>.

942 Shang, Y., Yang, Z., Li, L., Liao, Q., Wang, Y., 2003. A super-large landslide in Tibet in 2000:  
943 background, occurrence, disaster, and origin. *Geomorphology* 54(3-4), 225-243.  
944 [https://doi.org/10.1016/S0169-555X\(02\)00358-6](https://doi.org/10.1016/S0169-555X(02)00358-6).

945 Shi, C., An, Y., Wu, Q., Liu, Q., Cao, Z., 2016. Numerical simulation of landslide-generated  
946 waves using a soil–water coupling smoothed particle hydrodynamics model. *Adv. Water*  
947 *Resour.* 92, 130-141. <https://doi.org/10.1016/j.advwatres.2016.04.002>

948 Si, P., Aaron, J., McDougall, S., Lu, J., Yu, X., Roberts, N. J., Clague, J. J., 2018. A  
949 non-hydrostatic model for the numerical study of landslide-generated waves. *Landslides*  
950 15(4), 711-726. <https://doi.org/10.1007/s10346-017-0891-y>.

951 Skvortsov, A., Bornhold, B., 2007. Numerical simulation of the landslide generated tsunami  
952 in Kitimat Arm, British Columbia, Canada, 27 April 1975. *J. Geophys. Res.- Earth Surf.*  
953 112, F02028. <https://doi.org/10.1029/2006JF000499>.

954 Temple, D. M., Hanson, G. J., Neilsen, M. L., Cook, K. R., 2005. Simplified breach analysis  
955 model for homogeneous embankments: Part I, Background and model components, in:  
956 *Proc. 25th Annual U.S. Society on Dams Conference, Denver*, pp. 151-161.

957 United States Army Corps of Engineers (USACE), 2016. HEC-RAS, River Analysis System -  
958 Hydraulic Reference Manual (Version 5.0).  
959 <https://www.hec.usace.army.mil/software/hecras/documentation.aspx> (accessed 23 May  
960 2020).

961 Van Asch, T. W., Buma, J., Van Beek, L. P. H., 1999. A view on some hydrological triggering  
962 systems in landslides. *Geomorphology* 30(1-2), 25-32.  
963 [https://doi.org/10.1016/S0169-555X\(99\)00042-2](https://doi.org/10.1016/S0169-555X(99)00042-2).

964 Vetsch, D., Siviglia, A., Ehrbar, D., Facchini, M., Kammerer, S., Koch, A., Peter, S.,  
965 Vonwiller, L., Gerber, M., Volz, C., Farshi, D., Mueller, R., Rousselot, P., Veprek, R.,  
966 Faeh, R., 2018. System Manuals of BASEMENT, Version 2.8.  
967 <http://www.basement.ethz.ch> (accessed 23 May 2020).

968 Walder, J. S., O'Connor, J. E., 1997. Methods for predicting peak discharge of floods caused  
969 by failure of natural and constructed earthen dams. *Water Resour. Res.* 33(10),  
970 2337-2348. <https://doi.org/10.1029/97WR01616>.

971 Wang, W., Chen, G., Zhang, Y., Zheng, L., Zhang, H., 2017. Dynamic simulation of landslide  
972 dam behavior considering kinematic characteristics using a coupled DDA-SPH method.  
973 *Eng. Anal. Bound. Elem.* 80, 172-183.  
974 <https://doi.org/10.1016/j.enganabound.2017.02.016>.

975 Wang, W., Yin, K., Chen, G., Chai, B., Han, Z., Zhou, J., 2019. Practical application of the

976 coupled DDA-SPH method in dynamic modeling for the formation of landslide dam.  
 977 Landslides 16(5), 1021-1032. <https://doi.org/10.1007/s10346-019-01143-5>.

978 Wang, G., Liu, F., Fu, X., Li, T., 2008. Simulation of dam breach development for emergency  
 979 treatment of the Tangjiashan Quake Lake in China. *Sci. China Technol. Sci.* 51(2), 82-94.  
 980 <https://doi.org/10.1007/s11431-008-6019-9>.

981 Wang, Z., Bowles, D. S., 2006a. Three-dimensional non-cohesive earthen dam breach model.  
 982 Part 1: Theory and methodology. *Adv. Water Resour.* 29(10), 1528-1545.  
 983 <https://doi.org/10.1016/j.advwatres.2005.11.009>.

984 Wang, Z., Bowles, D. S., 2006b. Three-dimensional non-cohesive earthen dam breach model.  
 985 Part 2: Validation and applications. *Adv. Water Resour.* 29(10), 1490-1503.  
 986 <https://doi.org/10.1016/j.advwatres.2005.11.010>.

987 Wilcock, P. R., 1997. Entrainment, displacement and transport of tracer gravels. *Earth Surf.*  
 988 *Proc. Land.* 22 (12), 1125–1138. [http://dx.doi.org/10.1002/\(SICI\)](http://dx.doi.org/10.1002/(SICI)1096-9837(199712)22:12<1125)  
 989 [1096-9837\(199712\)22:12 <1125](http://dx.doi.org/10.1002/(SICI)1096-9837(199712)22:12<1125) .

990 Worni, R., Huggel, C., Clague, J. J., Schaub, Y., Stoffel, M., 2014. Coupling glacial lake  
 991 impact, dam breach, and flood processes: A modeling perspective. *Geomorphology* 224,  
 992 161-176. <https://doi.org/10.1016/j.geomorph.2014.06.031>.

993 Wu, W., 2013. Simplified physically based model of earthen embankment breaching. *J.*  
 994 *Hydraul. Eng.* 139(8), 837-851. [https://doi.org/10.1061/\(ASCE\)HY.1943-7900.0000741](https://doi.org/10.1061/(ASCE)HY.1943-7900.0000741).

995 Wu, W., Marsooli, R., He, Z., 2012. Depth-averaged two-dimensional model of unsteady  
 996 flow and sediment transport due to noncohesive embankment break/breaching. *J.*  
 997 *Hydraul. Eng.* 138(6), 503-516. <https://doi.org/10.1029/2017WR022492>.

998 Wu, Y., Fang, H., Huang, L., Ouyang, W., 2020. Changing runoff due to temperature and  
 999 precipitation variations in the dammed Jinsha River. *J. Hydrol.* 582, 124500.  
 1000 <https://doi.org/10.1016/j.jhydrol.2019.124500>.

1001 Xu, Q., Fan, X. M., Huang, R. Q., Van Westen, C., 2009. Landslide dams triggered by the  
 1002 Wenchuan Earthquake, Sichuan Province, south west China. *Bull. Eng. Geol. Environ.*  
 1003 68(3), 373-386. <https://doi.org/10.1007/s10064-009-0214-1>.

1004 Xu, W. J., Yao, Z. G., Luo, Y. T., Dong, X. Y., 2020. Study on landslide-induced wave  
 1005 disasters using a 3D coupled SPH-DEM method. *Bull. Eng. Geol. Environ.* 79(1),  
 1006 467-483. <https://doi.org/10.1007/s10064-019-01558-3>.

1007 Xu, Y., Zhang, L. M., 2009. Breaching parameters for earth and rockfill dams. *J. Geotech.*  
1008 *Geoenviron. Eng.* 135(12), 1957-1970.  
1009 [https://doi.org/10.1061/\(ASCE\)GT.1943-5606.0000162](https://doi.org/10.1061/(ASCE)GT.1943-5606.0000162).

1010 Zhao, T., Dai, F., Xu, N. W., 2017. Coupled DEM-CFD investigation on the formation of  
1011 landslide dams in narrow rivers. *Landslides* 14(1), 189-201.  
1012 <https://doi.org/10.1007/s10346-015-0675-1>.

1013 Zhang, L., Xiao, T., He, J., Chen, C., 2019. Erosion-based analysis of breaching of Baige  
1014 landslide dams on the Jinsha River, China, in 2018. *Landslides* 16(10), 1965-1979.  
1015 <https://doi.org/10.1007/s10346-019-01247-y>.

1016 Zhang, Y., Meng, X. M., Dijkstra, T. A., Jordan, C. J., Chen, G., Zeng, R. Q., Novellino, A.,  
1017 2020. Forecasting the magnitude of potential landslides based on InSAR techniques.  
1018 *Remote Sens. Environ.* 241, 111738. <https://doi.org/10.1016/j.rse.2020.111738>.

1019 Zhang, Z., He, S., Liu, W., Liang, H., Yan, S., Deng, Y., Bai, X. Chen, Z., 2019. Source  
1020 characteristics and dynamics of the October 2018 Baige landslide revealed by broadband  
1021 seismograms. *Landslides* 16(4), 777-785. <https://doi.org/10.1007/s10346-019-01145-3>

1022 Zhong, Q., Chen, S., Wang, L., Shan, Y., 2020. Back analysis of breaching process of Baige  
1023 landslide dam. *Landslides*, in press. <https://doi.org/10.1007/s10346-020-01398-3>

1024 Zitti, G., Ancey, C., Postacchini, M., Brocchini, M., 2016. Impulse waves generated by snow  
1025 avalanches: momentum and energy transfer to a water body. *J. Geophys. Res.- Earth Surf.*  
1026 121(12), 2399-2423. <https://doi.org/10.1002/2016JF003891>.

1027

1028 **List of figure captions**

1029

1030 **Fig. 1.** Location of Baige barrier lake, Jinsha River, China (adapted from Fan et al., 2020a):  
1031 (a) upstream areas inundated by barrier lake; (b) towns affected by downstream flooding (the  
1032 orange box indicates the study area).

1033

1034 **Fig.2.** “10.10” Baige barrier lake: (a) formation; (b) after breaching. (photo courtesy of  
1035 Chinanews.com).

1036

1037 **Fig. 3.** “11.03” Baige barrier lake: (a) formation; (b) with artificial flood channel; (c) during  
1038 breaching; (d) after breaching (photo courtesy of a CCTV.com; b Red Star News; c Ministry  
1039 of Emergency Management of China; d L. Zhang et al., 2019).

1040

1041 **Fig. 4.** Phase I “10.10” Baige landslide impacting Jinsha river: model predictions of landslide  
1042 velocity field at times  $t =$  (a) 5 s, (b) 10 s, (c) 20 s, (d) 40 s, (e) 100 s, and (f) 900 s.

1043

1044 **Fig. 5.** Phase I “10.10” Baige landslide-generated waves: predicted water level hydrographs  
1045 at three locations in the Jinsha river near Baige, Sichuan, China.

1046

1047 **Fig. 6.** “10.10” Baige landslide dam geometry: (a) bed deformation at  $t = 900$  s predicted  
1048 by present model; and (b) cross-section profile of landslide dam in the original river  
1049 stream-wise direction (A-A’): model prediction (solid line) and measured data from Fan et al.  
1050 (2020a) (dashed line).

1051

1052 **Fig. 7.** “10.10” Baige landslide dam and barrier lake formation: (a1-a6) depth of water layer;  
1053 (b1-b6) landslide thickness; and (c1-c6) bed deformation.

1054

1055 **Fig. 8.** (a) Breaching flow discharge hydrograph and (b) flow discharge hydrograph and  
1056 sediment volume output time series at the Yabatan gauging station: model predictions (solid  
1057 lines) and measured data from Cai et al. (2019) (open black circles).

1058

1059 **Fig. 9.** Water level time series at the barrier lake and selected sites downstream of the “10.10”  
1060 Baige landslide dam.

1061

1062 **Fig. 10.** “10.10” Landslide-induced barrier lake outburst and the resultant flood: (a1-a6)  
1063 depth of water layer; (b1-b6) water-sediment mixture thickness; and (c1-c6) bed deformation.  
1064 (a1, b1 and c1) Landslide dam is overtopped naturally and dam breach commences. (a2, b2  
1065 and c2) Breaching flow arrives at Yebatan. (a3, b3 and c3) Breaching flow discharge is  
1066 almost equivalent to upstream inflow discharge. (a4, b4 and c4) Breaching flow peaks. (a5,  
1067 b5 and c5) Peak breaching flow arrives at Yebatan. (a6, b6 and c6) Jinsha river resumes its  
1068 base flow and the dam breach process terminates.

1069

1070 **Fig. 11.** Contour plots of velocity difference between water and sediment phases of the  
1071 water-sediment mixture flow layer in the transverse ( $y$  – axis) direction at different times  
1072 from 10 s to 55.75 hr after the start of the “10.10” Baige landslide: a1–a5 with  $d = 1$  mm;  
1073 and b1–b5 with  $d = 20$  mm.

1074

1075 **Fig. 12.** Contour plots of velocity difference between water and sediment phases of the  
1076 water-sediment mixture flow layer in the longitudinal ( $x$  – axis) direction at different times  
1077 from 10 s to 55.75 hr after the start of the “10.10” Baige landslide, a1-a5 with  $d = 1$  mm,  
1078 and b1-b5 with  $d = 20$  mm.

1079

1080 **Fig. 13.** Model predictions of breaching flow discharge hydrographs for three different Jinsha  
1081 river inflow discharges.

1082

1083 **Fig. 14.** Model predictions of breaching flow discharge hydrographs for three different initial  
1084 landslide volumes.

1085

1086 **Fig. 15.** “10.10” Baige landslide dam morphology assuming different bed friction coefficient  
1087  $\tan \delta$  (a1-a3) bed deformation at  $t = 900$  s predicted by present model; and (b1-b3)  
1088 cross-section profile of landslide dam in the original river stream-wise direction (A-A’):  
1089 model prediction (solid line) and measured data from Fan et al. (2020a) (dashed line).

1090  
1091  
1092  
1093  
1094  
1095  
1096  
1097  
1098  
1099  
1100  
1101  
1102  
1103  
1104  
1105  
1106  
1107  
1108  
1109  
1110  
1111  
1112  
1113  
1114  
1115  
1116  
1117

**Fig. 16.** “10.10” Baige landslide dam morphology assuming different Manning roughness coefficient  $n_b$  (a1-a3) bed deformation at  $t = 900$  s predicted by present model; and (b1-b3) cross-section profile of landslide dam in the original river stream-wise direction (A-A’): model prediction (solid line) and measured data from Fan et al. (2020a) (dashed line).

**Fig. 17.** Model predictions (solid lines) of breaching flow discharge hydrographs assuming (a) different bed friction coefficient  $\tan \delta$ ; and (b) different Manning roughness coefficient  $n_b$  and measured data (open circles) from Cai et al. (2019).

**Fig. 18.** “11.03” Baige landslide dam geometry: (a) predicted bed deformation contours at  $t = 900$  s; and (b) predicted (solid line) and measured (dashed line, Fan et al. 2020a) cross-sectional profiles of the landslide dam in a longitudinal direction along the river (B-B’).

**Fig. 19.** (a) Breaching flow discharge hydrograph and water level time series at the “11.03” Baige landslide dam site; (b) flow discharge hydrograph and sediment volume output series at Yebatan (the downstream station): model predictions (solid lines) and measured data (open circles).

**Fig. 20.** “11.03” Baige landslide dam breach evolution depicted as bed deformation contours and superimposed flow velocity vectors at post-landslide times,  $t =$ : (a) 202.75 hr; (b) 206.75 hr; (c) 230.75 hr; (d) 235.75 hr; (e) 240.2 hr; and (f) 260.0 hr.

**Fig. 21.** Model predictions of breaching flow discharge hydrographs (blue) and barrier lake level time series (red): scenario with artificial flood channel (dashed lines); and scenario without an artificial flood channel (solid lines).

1118 **List of table captions**

1119

1120 **Table 1** “10.10” Baige landslide-generated wave run-up on the opposite bank

1121

1122 **Table 2** Summary of “10.10” Baige landslide dam morphology

1123

1124 **Table 3** Predicted effect of inflow discharge on landslide dam formation, overtopping, and  
1125 breaching processes (Series 1 tests)

1126

1127 **Table 4** Predicted effect of inflow landslide volume on landslide dam formation, overtopping,  
1128 and breaching processes (Series 2 tests)

1129

1130 **Table 5** Summary of  $L^1$  norms of model prediction for Baige barrier lake events

1131