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Interactive comment on "State of the Art Study of Influence of Bed Roughness and Alluvial Cover on Bedrock Channels and Comparisons of Existing Models with Laboratory Scale Experiments" *by* Jagriti Mishra and Takuya Inoue

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We thank the reviewers for their constructive feedback and comments on our manuscript.

One general point is that the introduction and section on models could be more clearly structured. For example, the introduction covers a range of very relevant papers, but is mainly a summary of each of them, and they seem to be presented in a fairly arbitrary order. For example, Johnson et al (2010) and Finnegan et al (2007) are reported as

having similar findings, but they are presented in different sections of the introduction. It would be useful to outline more clearly what some of the key debates have been, and show how the different papers have contributed to these debates. Further specific comments are below. AC: We have made changes as suggested. 1 Introduction Economic growth worldwide has fuelled the demand for the construction of straightened river channels, sabo dams, the collection of gravel samples for various research, etc., leading to a decline in sediment availability and alluvial bed cover. Sumner et al. (2019) reported that the straightening of the Yubari River, which was carried out to improve the drainage of farmland, caused the bedrock to be exposed and the knickpoint to migrate upstream. In addition, construction of a dam in the upstream section of Toyohira river in Hokkaido – Japan, decreased the sediment availability to the downstream section contributing to the formation of a knickpoint (Yamaguchi et al. 2017 in Japanease). Sediment availability plays a very important role in controlling the landscape evolution and determining the morphology of the river over geologic time (Moore 1926; Shepherd 1972). Various field-scale (Gilbert, 1877; Shepherd, 1972; Turowski et al., 2008b; Turowski and Rickenmann, 2009; Johnson et al., 2010; Jansen et al., 2011; Cook et al., 2013; Inoue et al., 2014; Beer and Turowski, 2015; Beer et al., 2017), laboratory-scale (Sklar and Dietrich, 1998, 2001; Chatanantavet and Parker, 2008; Finnegan et al., 2007; Johnson and Whipple, 2010, 2007; Hodge and Hoey, 2016a, 2016b; Hodge et al., 2016; Turowski and Bloem, 2016; Inoue et al., 2017b, Mishra et al., 2018; Fernandez et al., 2019; Inoue and Nelson, 2020), and theoretical and numerical studies (Hancock and Anderson, 2002; Sklar and Dietrich, 2004, 2006; Lague, 2010; Hobley et al., 2011; Nelson and Seminara, 2011, 2012; Johnson, 2014; Nelson et al., 2014; Zhang et al., 2015; Inoue et al. 2016, 2017a; Turowski and Hodge 2017; Turowski, 2018) have suggested that sediment availability has two contradicting effects on the river bed, known as Tools and Cover effect. It acts as a tool and erodes the bedrock bed, known as tools effect. As sediment availability increases, the sediment starts settling down on the river bed providing a cover for the bed underneath from further erosion, known as the cover effect. Sklar and Dietrich (2001) and Scheingross et al.,

(2014) performed rotary-abrasion mill experiments showing the importance of cover in controlling incision rates in bedrock channels. Reach scale studies of Erlenbach performed by Turowski et al. (2013) showed how extreme flood events can contribute to incision by ripping off the channel's alluvial cover. Cook et al. (2013) suggested that bedrock incision rates were dominantly controlled by the availability of bedload. Their field surveys of bedrock gorge cut by Daán River in Taiwan showed that the channel bed merely eroded for years, despite floods and available suspended sediment. Channel incision occurred only when bedload tools became available. Yanites et al. (2011) studied the changes in the Peikang River in central Taiwan triggered by the thick sediment cover introduced by landslides and typhoons during the 1999 Chi-Chi earthquake. Their results show slowed or no incision in high transport capacity and low transport capacity channels. Mishra et al. (2018) showed that incision rate increased when the sediment supply rate of the laboratory-scale channel became considerably smaller than the sediment carrying capacity of the channel. Laboratory scale experiments performed by Shepherd and Schumm (1974), Wohl and Ikeda (1997) and Inoue and Nelson (2020) showed formation of several longitudinal grooves at low sediment supply to capacity ratio. As the sediment supply increases, one of the grooves attracts more sediment supply and progresses into a comparatively straight, wide and shallow inner channel which further progresses into a narrower, more sinuous, deeper inner channel (Wohl and Ikeda, 1997; Inoue et al., 2016). Channels with higher sediment supply to capacity ratio are expected to be wider as alluvial cover shifts erosion from bed to banks of the channel (Beer et al. 2016; Turowski et al., 2008a and Whitbread et al., 2015). These findings show the ratio of sediment supply to capacity controls alluvial cover ratio, bedrock incision rate and morphodynamics in bedrock rivers. Finnegan et al. (2007) conducted laboratory-scale experiments and studied the interdependence among incision, bed roughness and alluvial cover. Their results indicated that alluvial deposition on the bed shifted bed erosion to higher regions of the channel or bank of the channel. Similar findings were noted in flume studies conducted by Wohl and Ikeda (1997) and Johnson and Whipple (2010). They have shown the importance of

alluvial cover in regulating the roughness of bedrock bed by providing a cover for the local lows and thereby inhibiting the erosion and focusing erosion on local highs. Inoue et al. (2014) conducted experiments by excavating channel into natural bedrocks in Ishikari River, Asahikawa, Hokkaido – Japan. They conducted experiments with different combinations of flow discharge, sediment supply rate, grain size and roughness. Their experiments advocated that the dimensionless critical shear stress for sediment movement on bedrock is related to the roughness of the channel. Their experiments also suggested that with an increase in alluvial cover, the relative roughness (i.e., the ratio of bedrock hydraulic roughness to moving sediment size) decreases, also, erosion in areas with an exposed bed is proportionate to sediment flux. Fuller et al. (2016) performed laboratory scale experiments and established the importance of bed-roughness in determining the incision and lateral erosion rates. Chatanantavet and Parker (2008) conducted laboratory-scale experiments in straight concrete bedrock channels with varying bedrock roughness and evaluated bedrock exposure with respect to sediment availability. In their experiments, alluvial cover increased linearly with increasing sediment supply in case of higher bed roughness, whereas in case of lower bed roughness and higher slopes, the bed shifted abruptly from being completely exposed to being completely covered. This process of the bedrock bed suddenly becoming completely alluvial from being completely exposed is known as rapid alluviation. Rapid alluviation was also observed in the laboratory scale experiment conducted by Hodge and Hoey (2016a; 2016b) in a 3D printed flume of natural stream Trout Beck, North Pennies-U.K. Their first set of experiments focused on quantifying hydraulic change with varying discharge, suggesting that hydraulic properties fluctuate more during higher discharge. Their second set of experiments (Hodge and Hoey, 2016b) concentrated on quantifying the sediment dynamics for varying discharge and sediment supply. They supplied 4 kg and 8 kg of sediment pulse to the channel and observed a similar alluvial pattern in both cases suggesting that the deposition of sediment on the bed may not only depend on the amount of sediment supplied, but may be strongly influenced by the bed topography and roughness. The latest studies of alluvial cover in bedrock rivers have entered the next stage, which includes not only the effect of sediment supply-capacity ratio but also the effect of bed roughness. A majority of traditional bed-erosion models are classified as the stream power and shear stress family of models (cf. Shobe et al., 2017; Turowski, 2018) (e.g., Howard, 1994; Whipple and Tucker, 1999), in which bed erosion is a function of discharge and bed-slope. These models however cannot describe the role of sediment in controlling the bed dynamics. Several models remedy this shortcoming by considering the tools and cover effect of sediment supply (Sklar and Dietrich, 1998, 2004; Turowski et al., 2007; Chatanantavet and Parker, 2009; Hobley et al., 2011; Inoue et al., 2017b). In section 1.1, we introduce previous theoretical and numerical models that take into account sediment cover in bedrock channel. In sections 1.2 to 1.6, we describe in detail the governing equations of the five models dealt with in this study.

An interesting aspect of this paper is the calculation of roughness lengths by minimizing the differences between the models and the experimental results. I would like to see further consideration of how these roughness lengths compare to the measured hydraulic roughness lengths. The need to alter roughness lengths for the models suggests that the models are not accurately reproducing all aspects of the processes in the channel. What are the models missing? It may also suggest that the way in which roughness lengths are calculated by Johnson's model is incorrect. Can you say any more about this, and maybe make recommendations for how the models could be improved and roughness lengths should be calculated? A recent paper by Ferguson et al (2019) addresses how to calculate roughness lengths in bedrock-alluvial channels with multiple roughness length scales, and might be of interest. AC: we have added limitations and future developments.

As mentioned earlier, the major difference between the macro-roughness model (Inoue et al., 2014) and surface-roughness model (Johnson., 2014) is the way the transport capacity is calculated. In case of the surface-roughness model (Johnson, 2014), first, the transport capacities for bedrock (q_bcb) and alluvial bed (q_bca) are separately calculated, then the total transport capacity (q_bc) is calculated for a range of cover fractions (P_c). Hence, in cases when τ_(*ca)<τ_*<τ_(*cb), the transport capacity over bedrock portion q_bcb=0 and thereby the bedrock roughness hardly affects the alluvial cover fraction which can also be the reason for inconsistency between the surface-roughness model (Johnson, 2014) results and experimental study for Runs 1 and 4 in Figure 11 and RA2 Slope = 0.0115 in Figure 13. Whereas, in the case of macro-roughness model (Inoue et al., 2014), the critical shear stress takes into account the value of total hydraulic roughness, which depends on cover fraction, alluvial hydraulic roughness and bedrock hydraulic roughness. Hence, even when τ_* is small, the bedrock roughness tends to affect the cover fraction. The macro-roughness model (Inoue et al., 2014) is more efficient at dealing with clast-smooth surfaces. Comparing the observed k_sb with the adjusted k_sb in the roughness models proposed by Inoue et al. (2014) and Johnson (2014), the adjusted ksb strongly depends on observed k_sb in our experiments without alternate bars (Figure 14a), whereas, the adjusted k_sb is not dependent on the observed k_sb in experiments with alternate bars conducted by Chatanantavet and Parker (2008) (Figure 14b), suggests that bedrock roughness has a smaller effect on the alluvial cover in case of mixed alluvial – bedrock rivers with alternate bars. In such rivers, the bed slope may affect the alluvial cover fraction (Figure 14c). The roughness models are adjusted to produce the experimental results with alternate bars by fine-tuning r_br and k_sb values which must be determined by trial and error method. While this method can be applicable to laboratory-scale experiments, the model calibration is unfeasible for a large-scale channel or natural rivers. In general, the formation of alternate bars is barely reproduced with a one-dimensional model as introduced in this study. In the future, research to incorporate the effects of bars into a one-dimensional model, or analysis using a two-dimensional planar model (e.g., Nelson and Seminara, 2012; Inoue et al., 2016, 2017) is expected. Also, in order to deploy models on field-scale, they must take into account bank-roughness and its effects on shear stress and other hydraulic parameters. Ferguson (2019) argued that standard deviation of exposed bed is an effective way of roughness estimation, however, it needs further research on appropriating scaling. Also, the probabilistic model proposed by Turowski and Hodge (2017) could reproduce experimental results but the model needed adjustment of ω and M_0ˆ* by trial and error, especially for cases involving rapid alluviation. The model however does not emulate the hysteresis for clast-smooth beds. Because the model does not include the effects of bed roughness yet, further alterations to take into account the effect of probability of grain entrainment and deposition can greatly extend the applicability of the model to natural bedrock rivers. In addition, recently, Turowski (2020) proposed a stochastic model that includes the effects of bar formation, and further development is expected in the future. Taking into account the spatial variability in the tools effect (laboratory experiments by Bramante et al., 2020) will also take the models closer to field-scale studies.

Throughout, it would be helpful to name the experimental runs in a way that describes the bed roughness, such as Gravel50, or Net4. When they are all called Run it is harder to remember which is which. We renamed cases as per your suggestion. Thank you!

Comments by line:

1: No need to include state of the art in title. I would reword the title as the influence of bed roughness and sediment supply on the alluvial cover in bedrock channels. We changed the title as suggested : The Influence of Bed Roughness and Sediment Supply on Alluvial Cover in Bedrock Channels

7: Abstract needs to be clear that this paper is focussing on bedrock channels. Line 7: We have mentioned it. Several studies have implied towards the importance of bedrock-bed roughness on alluvial cover; besides, several mathematical models have also been introduced to mimic the effect bed roughness may project on alluvial cover in bedrock channels. Here, we provide an extensive review of research exploring the relationship between alluvial cover, sediment supply and bed topography of bedrock channels, thereby, describing various mathematical models used to analyse deposition of alluvium. In the interest of analysing the efficiency of various available mathemat-

ical models, we performed a series of laboratory-scale experiments with varying bed roughness and compared the results with various models. Our experiments show that alluvial cover is not merely governed by increasing sediment supply, and, bed topography is an important controlling factor of alluvial cover. We tested five theoretical models with the experimental results and the results suggest a fit of certain models for a particular bed topography and inefficiency in predicting higher roughness topography. Three models efficiently predict the experimental observations, albeit their limitations.

11: Add more details about the experiments that you carried out. Line 12: We have made some changes. Please see #7.

18: Interesting idea that economic growth has increased the occurrence of bedrock channels; do you have any evidence for this? Line 19: Sumner et al. (2019) reported that the straightening of the Yubari River, which was carried out to improve the drainage of farmland, caused the bedrock to be exposed and the knickpoint to migrate upstream. In addition, construction of a dam in the upstream section of Toyohira river in Hokkaido – Japan, decreased the sediment availability to the downstream section contributing to the formation of a knickpoint (Yamaguchi et al. 2017 in Japanease).

22: Sediment cover can start to form when sediment supply is less than the transport capacity. Line 32: We changed the sentence As sediment availability increases, the sediment starts settling down on the river bed providing a cover for the bed underneath from further erosion, known as the cover effect.

28: However, see also Cook et al. (2013) in which no erosion occurred when there was no sediment supply. Line 36: We added this study in the manuscript. Cook et al. (2013) suggested that bedrock incision rates were dominantly controlled by the availability of bedload. Their field surveys of bedrock gorge cut by Daán River in Taiwan showed that the channel bed merely eroded for years, despite floods and available suspended sediment. Channel incision occurred only when bedload tools became available.

30: See also some of Turowski's work about the amount of cover determining the elevation of erosion, e.g. Turowski et al. (2008). We added this work in the manuscript. Please see 1.Introduction

37: This relationship depends on the relative roughness of the bed and the sediment though. Line 59: Changed to relative roughness

86: Specify that it is the critical shear stress for sediment movement. Is this for grains in sediment patches, or on bedrock? Line 58: Mentioned. It is for grains on bedrock

97: Is L is the macro-roughness height of just the bedrock? Line 154: Yes. We mentioned it in the new manuscript

107: By deposition, do you mean Pc? Line 164: Yes. We mentioned.

109: New model, so start a new paragraph. Section 1.3: Changed accordingly. We dedicated separate sections to each model.

126: Not entirely clear which two models you are referring to. Start the section by briefly presenting the two models before getting into the details of each. Line 187: Changed accordingly.

128: Can you only apply the Inoue model if you have measurements of both the alluvial and bedrock hydraulic roughness? What if you don't have them? If you had hydraulic roughness measurements then presumably you could substitute those into the Johnson model? Are there other differences between the models as well? Line 190-197: No, Inoue model needs only a obserbed bedrock hydraulic roughnes. Alluvial hydraulic roughnes is 2d, equal to Johnson (2014). Johnson's model can use the obeseved hydraulic rougness. In this case, however, the prediction accuracy is lower than the Inoue model. As noted in the text, the two models have slightly different methods for calculating the transport capacity.

135: Might be useful to explain how Turowski and Hodge's model is a probability-based model. Sec. 1.6: We tried to explain.

150: Explain more clearly what you mean by no-sandbar conditions. Are you getting no bars at all, or just not a certain type of bar? Later on you refer to alternate bars in Chatanantavet and Parker's experiments. Line: 253: The formation of bars strongly depends on the width – depth ratio (e.g., Kuroki and Kishi, 1984; Colombini et al., 1987). Generally. neither alternate bars nor double-row bars are formed under the condition with B/H < 15. Colombini, M., Seminara, G., & Tubino, M. (1987). FiniteâĂŘamplitude alternate bars, J. Fluid Mech., 181, 213– 232. doi: 10.1017/S0022112087002064 Kuroki, M., & Kishi, T. (1984). Regime criteria on bars and braids in alluvial straight channels, Proc. Japan Soc. Civil Eng., 342, 87-96. doi: 10.2208/jscej1969.1984.342_87 (in Japanese)

159: What is the net made from? Line 232: Plastic

180: State that these measurements were performed for all 5 surfaces. It might also be useful to explain why you use 5 mm gravel here, but sand in the rest of the experiments. Line 268: Thank you for kind suggestion. We have added that the measurements were performed for all 5 bedrock surfaces. We wrote sand by mistake. Sorry. We used 5mm gravek for carrying out all the experiments.

187: What is the grain size of the sand? There is a lot of variation in the supply rates between the different experiments; how did you decide what range of supply rates to use for each bed?

We have used the same gravel everywhere. 5mm gravel was used for conducting the experiments. Line 277: For each roughness condition, initially, we supplied sediment at the rate of 3.73x10-5m2/s and observed the evolution of Pc. If Pc$\approx$1, we reduced the sediment supply by approximately 1.5 times in the subsequent run, and then the reduced the sediment supply to 2 times and 4 times (example: Gravel30, Gravel50 and Net4). In roughness conditions where sediment supply of 3.73x10-5m2/s resulted in Pc$\approx$0, the sediment supply was increased by 1.25 or 1.5 times and 2 times in the subsequent runs (example: Gravel5 and Net2). However, for ease of understanding, we will present each experimental run in ascending order by sediment supplied.

188: How was equilibrium state defined?

Line 269: Once the areal fraction became stable in qualitative observations despite sediment being supplied, we considered that the experiment has reached its equilibrium state. Also, the observed water level was also a factor in the judgment. In Figure 7 it can be seen that with time, the roughness variation in each case is decreasing.

193: How often was the alluvial cover calculated? only at the end of the experiment

196: Add a column onto Table 1 to include the hydraulic roughness of each experiment. Added in Table 1.

230: In the Fig 3 caption, explain that the bedrock bed is white and sediment is dark. Made changes as suggested

242: How do you measure the average thickness of the alluvial layer? The methods mention measuring the topography of the bedrock bed, but not measuring the topography once sediment cover has been added.

Line 286: Bedrock topography with alluvial cover was also measured with a laser sand gauge. Since bedrock topography without alluvial cover have been measured in section 2.3, we can calculate the alluvial thickness from the diffarence of two data.

243: I had to look up what this equals sign meant; I don’t think that it’s commonly used in Europe. Changed to “$\approx$”

245: Still not clear where the thickness values have come from. Is the average thickness evaluated across the entire bed (so that it includes areas where the thickness is zero), or just the areas with sediment cover? I’m also not sure how to interpret Fig 6. If the average thickness includes areas with zero cover, then _a/L could increase because the cover is growing spatially, but with the depth of all sediment cover remaining the same. The other extreme would be that the spatial extent of the cover doesn’t

change, but the depth of any existing cover increases. What is the relative contribution of lateral vs. vertical growth of the sediment cover to the increasing average depth? Pc is the value calculated from the photo (Figures 3 and 4). ηa is the spatial average value of the alluvial layer thickness calculated from the difference between the two topographic data. Of course, the part without alluvial cover is treated as zero. L is the spatial average value of the standard deviation of the unevenness of the bedrock without alluvial cover. As you pointed out, there are some special cases, such as when the thickness only increases. We also initially doubted the accuracy of macro-roughness model, and simply used the spatial average values in the window with 5 m length and 0.5 m wide which were used for estimating pc. As a result, although the macro roughness model can roughly predict pc, there were variations as shown in Fig. 6.

253: Is the relative roughness referred to here calculated from the hydraulic roughness length? > yes. It would be interesting to see how it varies as the bed transitions from bedrock to alluvial. The changes over time in Fig. 7 are interesting, but it’s hard to compare the equilibrium conditions with different Pc values. I think that more could be done with these data, e.g. plotting ks/d against Pc for the different runs.

Please see Section 3.5 and Figure 8.

Figure 8 (attached)shows the variation in Pc with respect to relative roughness. In cases with lower initial relative roughness, example: Gravel 50 and Net2, the relative roughness is increasing with an increase in Pc. Whereas, in cases with higher initial relative roughness, Gravel30, Gravel5 and Net4, an increase in Pc reduces the relative roughness. Besides, irrespective of the initial relative roughness, the bed tries to become completely alluvial as Pc $\approx$ 1. Furthermore, irrespective of the initial relative roughness, an increase in Pc forces each roughness condition to achieve a similar stabilised roughness. Also, several studies in the past have suggested that when bed consists of a uniform grain size and also comprises of bedload consisting of uniform and same size grains as the cover, the hydraulic roughness height (ks) for such a bed is 1 to 4 times the grain diameter (d) (Inoue et al., 2014; Kamphuis, 1974; Parker, 1991) which is also the case in our experiments in Figure 8.

270: State that these grain sizes are different to those of the previous results. The grain size (d) in case of Inoue et al., (2013) is 5mm. and Inoue et al., 2014 used gravels sized: 12mm and 28mm. Mentioned in caption of Figure9.

281: In the legend it would be useful to label the equation 5 and 10 lines with the papers that they come from. Changed as per the suggestion

289: Be clear what you are minimising the RMSD between; I assume that it's the amount of sediment cover? Line 383: Yes, it is minimizing the RMSD of cover between experiment and model results.

291: Is this parameter calibrated in the same way? Line 386: Yes, by trial and error to reproduce the experimental results.

328 and 329: Again, specify what you are minimising the RMSD of. Line 453: Specified

345: What is τ_ *c referring to here? I'm confused because I would expect the bedrock critical shear stress to be less than the alluvial or combined critical shear stresses. Line 467: This was typographical error. We meant t*ca, referring to alluvial beds

345: I don't follow the sentence starting 'As a result..'. Modified the sentence:

Line 454: Hence, in cases when τ_(*ca)<τ_*<τ_(*cb), the transport capacity over bedrock portion q_bcb=0 and thereby the bedrock roughness hardly affects the alluvial cover fraction

389: I think that this is the first explicit mention of the hydraulic roughness of the alluvial beds. See earlier comments about including more of these data. We have made changes as per your suggestion.

Interactive comment on Earth Surf. Dynam. Discuss., https://doi.org/10.5194/esurf-2019-78, 2020.

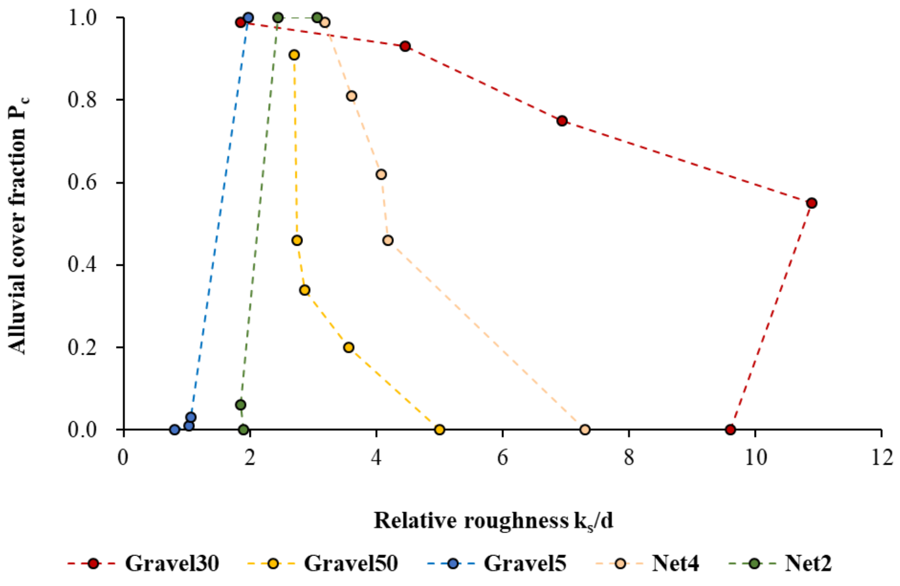

Fig. 1.