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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.

General comments: These could all be boiled down to one point, which is that the writing needs to be heavily restructured and expanded so that readers can understand and rigorously evaluate the work.

1) This is billed as a review paper, and indeed it has the potential to be a very nice

evaluation of several existing models. However, the portion of the paper that actually reviews previous work is extremely short. The entirety of the review is contained in less than 150 lines of text (section 1). For each model that the authors propose to evaluate, there should be a more complete description of how the model actually works, what any major assumptions are, what the key parameters are, and perhaps most importantly for this paper, what are the key predictions that each model makes that distinguish it from the others being evaluated. As an example, lines 116 to 125 present a very abbreviated description of Johnson's (2014) roughness model. I have read Johnson's paper two or three times over the years, and I still found this summary of their work hard to follow. The same goes for the work of Turowski and Hodge (2017). The quick summary of their work does not tell the readers almost anything about how their model was derived, except by some unspecified probabilistic approach. The papers being reviewed here are without exception very thorough pieces of work; each model description should be accompanied by at least a paragraph helping readers understand the model in greater detail, with specific reference to what diagnostic outcomes are expected from each one. Of course there is no need to re-do the derivations, but a little bit of extra explanation would go a long way to helping readers understand.

AC: Section 1: We have tried to improve the discussion as suggested by you and other reviewers.

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.

2) Along those same lines, there are really two different types of models being investigated here. There are the Inoue and Johnson models, which address the interplay between roughness and critical shear stress. Then there are the other models, which if I'm not mistaken look at sediment cover as a function of the ratio of sediment flux to transport capacity without dynamically modifying the critical shear stress. This fundamental distinction between model types is not clear in the introduction and review. Please see section 1.1: We have tried to improve the introduction part.

1.1 Previous Models for Sediment Cover One of the simplest and first models to incorporate effects of sediment availability and transport capacity of the channel was introduced by Sklar and Dietrich (1998; 2004). According to saltation-abrasion model proposed by Sklar and Dietrich (1998; 2004), the alluvial cover P_c increases linearly with the ratio of sediment supply to sediment transport capacity q_bs/q_bc , i.e. in absence of sediment supply, the alluvial cover is absent. However, when sediment supply becomes equal to or exceeds the transport capacity of the channel, the channel bed is fully covered. In order to express the non-linear relationship between P_c and q_bs/q_bc , Turowski et al. (2007) proposed a model that considered the cover effect as an exponential function of the ratio of sediment flux to sediment transport capacity. The model uses a probabilistic argument i.e., when sediment supply is less than the capacity of the channel, grains have an equal probability of settling down over any part of the bed. Also, the deposited grains can be static or mobile. These models however lack the statement of sediment mass conservation. A group of models utilise entrainment/deposition flux or Exner equation for sediment mass conservation (Turowski, 2009; Lague, 2010; Inoue et al., 2014;2016;2017; Nelson and Seminara, 2012; Hodge and Hoey, 2012; Johnson, 2014; Zhang, 2015; Turowski and Hodge, 2017). Turowski and Hodge (2017) generalized the arguments presented by Turowski et al. (2007) and Turowski (2009), and proposed a reach- scale probability-based model that can deal with the evolution of cover residing on the bed and the exposed bedrock. Turowski (2018) proposed a model and linked availability of cover in regulating the sinuosity of the channel. Lague (2010) employed Exner equation to calculate alluvial thickness with respect to average grain size d. Their model however lacks the tools effect for bed erosion. Recently, Johnson (2014) and Inoue et al. (2014) proposed reach-scale physically-based models that could encompass the effects of bed roughness in addition to alluvial thickness. Inoue et al. (2014) also conceptualised ‘Clast Rough’ and ‘Clast Smooth’ bedrock surfaces. A bedrock surface is clast-rough when bedrock hydraulic roughness is greater than the alluvial bed hydraulic roughness (supplied sediment), otherwise, a surface is clast-smooth i.e. when the bedrock roughness is lower than the alluvial roughness. Inoue et al. (2014) and Johnson (2014) clarified that the areal fraction of alluvial cover exhibits a hysteresis with respect to the sediment supply and transport ratio in a clast smooth bedrock channel. They described that along with rapid alluviation, perturbations in sediment supply can also lead to rapid entrainment. Whether the bed undergoes rapid alluviation or rapid entrainment is determined by the bed condition when perturbations in sediment supply occur. If the perturbations occur on an exposed bed, it undergoes rapid alluviation, conversely, when perturbations happen on an alluviated bed, it undergoes rapid entrainment. Zhang et al. (2015) proposed macro-roughness saltation-abrasion model (MRSA) in which cover is a function of alluvial thickness and macro-roughness height. Nelson and Seminara (2012) proposed a linear stability analysis model for the formation of alternate bars on bedrock bed. Inoue et al. (2016) expanded Inoue et al. (2014) to allow variations in the depth and width of alluvial thickness in the channel cross-section. They further modified the numerical model (Inoue et al., 2017a) and implemented the model to observe changes in a meander bend. Hodge and Hoey (2012) introduced reach-scale Cellular Automaton Model that assigned an entrainment probability to each grain. The assigned probability of each grain was decided by the number of neighbouring cells containing a grain. If five or more of total eight neighbouring cells contained grain, the grain was considered to be a part of the cover, otherwise, it was considered an isolated grain. They suggested that rapid alluviation occurred only in cases when isolated grains were more than the cover on the bed. Also, they advised a sigmoidal relationship between q_bs/q_bc and 1-P_c. Aubert et al. (2016) proposed a Discrete-Element Model where they determined P_c from the velocity distribution of the grains. If the velocity of a

grain is 1/10th or lower than the maximum velocity, the grain settles as cover on the bedrock surface. The model, however, cannot deal with non-uniform velocity fields and hence cannot predict results for varying alluvial cover. Except for the Lagrangian description models that track individual particles (i.e., Hodge and Hoey, 2012; Aubert et al., 2016), the Eulerian description models are roughly classified into four categories; the linear model proposed by Sklar and Dietrich (1998, 2004), the exponential model proposed by Turowski et al. (2007), the probabilistic model proposed by Turowski and Hodge (2017) and the roughness models proposed by Inoue et al. (2014), Johnson (2014), Nelson and Seminara (2012) and Zhang et al. (2015). In this study, we focus on a detailed study of the similarities and differences among the Eulerian description models proposed by Sklar and Dietrich (2004), Turowski et al. (2007), Inoue et al. (2014), Johnson (2014) and Turowski and Hodge (2017). We compare the efficacy of these models from comparisons with our experimental results. In addition, we apply the roughness models (Inoue et al., 2014; Johnson, 2014) to the experiments conducted by Chatanantavet and Parker (2008) in order to analyse the effect of bedrock roughness on alluvial cover in a mixed bedrock - alluvial river with alternate bars.

3) The methodology by which all relevant quantities are calculated is not clear. For example: how was k_sb calculated? Line 112 gives an expression for it, but it seems to me that if that expression was used, there would be a perfect correlation between sigma_br and k_sb because you just multiply by a couple of parameters. Then in section 2.3, Manning’s equation somehow comes into the calculation. Why is Manning’s n calculated? How is it used? If it is used to determine a bedrock roughness parameter, how are the weird dimensions of Manning’s n reconciled such that both quantities in Figure 2 are in meters? It may be that I am just not understanding, but I am familiar with this literature. If I don’t understand then other readers may also have trouble.

In our experiments, the hydraulic roughness height (ks) was calculated using Manning – Strickler relation and Maning’s velocity formula. k_s=(7.66n_m √g)ˆ6 n_m=1/U Dˆ(2/3) ãĂŰS_eãĂŮˆ(1/2) where n_m is the Manning’s roughness coefficient and U is the average velocity (U=Q/wD where U is the water discharge, w is the channel width, D is the water depth), S_e is the energy gradient.

The calculation method of ksb in line 112 (equation 6) is only used in the model proposed in Johnson model. We added the explanation, "This method for estimating k_sb applies only to Johnson's model. The method of calculating the observed value of k_sb is explained in the section 2.3."

The Manning-Strickler equation is widely used, but the dimensions cannot be matched. It is more accurate to use the logarithmic law, but we used Manning-Strickler equation for simplicity.

4) Similarly, the experimental methodology in general needs to be more thoroughly explained. Section 2.4 is a good example of this. Measuring the critical stress is important to ultimately testing Inoue's and Johnson's models, but line 185 for example is not clear at all about how the ultimate values used in figure 8 were measured/calculated.

We have revised to "To measure the dimensionless critical shear stress of grains on completely bedrock portion, i.e. τ_(*cb), 30 gravels of 5mm diameter each, were placed on the flume floor at intervals of 10 cm or more to make sure that there was no shielding effect between the gravels (there was shielding effect due to unevenness of the bedrock). Next, water flow was supplied at a flow discharge that no gravel moved, and was slowly increased to a flow discharge at which all the gravels moved. The water level and the number of gravels displaced were measured and recorded for each flow discharge. These measurements were performed for all the 5 bedrock surfaces. We calculated the dimensionless shear stress τ_* (=(DS_e)/Rd), here R is the specific gravity of the submerged sediment (1.65). We defined the critical shear stress was τ_(*cb) is the weight average of τ_* using the number of displaced gravels. "

5) Also on section 2: please consider stating very clearly in this section what the structure of your experimental design was. Meaning, what changed between each "run" in a given group (say, the set of "run1" experiments). From Table 1 I gather that each group

of runs is for a different roughness condition, and then the sediment feed rate was varied within each roughness condition, but information this fundamental to the paper should not have to be hunted down in a table. Line 239: We included the changes. For each bed roughness (example: Gravel50 series), a group of experiments with varying sediment supply were performed for different time durations.

6) It is in many cases not clearly why certain decisions were made (i.e., little explanation or justification is given). For example, why can't the other models be tested against Chatanantavet and Parker's results (Figure 11)? If there is some obvious reason, then that's fine and it can just be stated. As it is, it is hard to tell what the rationale was for many choices made in the experimental setup and analysis. For investigating the influence of bed roughness on the alluvial cover in a bedrock channel with alternate bars. we also compared the experimental results of Chatanantavet and Parker (2008) with the model results of the physically based models including interaction between roughness and alluvial cover (i.e., Inoue et al., 2014; Johnson, 2014).

7) For the results: there is a lot of information that is only defined very late in the paper that should be in the introduction/background. For example, the word "hysteresis" does not even appear in the earlier sections, but becomes a focus of much discussion later in the paper. Similarly, the definition of smooth and rough beds that appears in line 300 should be moved to very early in the paper. We have added Line 104-110: "Inoue et al. (2014) also conceptualised 'Clast Rough' and 'Clast Smooth' bedrock surfaces. A bedrock surface is clast-rough when bedrock hydraulic roughness is greater than the alluvial bed hydraulic roughness (supplied sediment), otherwise, a surface is clast-smooth i.e. when the bedrock roughness is lower than the alluvial roughness. Inoue et al. (2014) and Johnson (2014) clarified that the areal fraction of alluvial cover exhibits a hysteresis with respect to the sediment supply and transport ratio in a clast smooth bedrock channel."

8) Discussion/conclusions: The conclusions report what the study found, but they do not do an effective job of zooming out and telling readers how this improves our un-

derstanding of bedrock-alluvial river processes. What does it mean that both the Inoue and Johnson model can reproduce the experimental results? What is the implication of that fact that the Turowski and Hodge model can replicate the results, but needs some parameter adjustments? There's an opportunity here: the success (or not) of various models should tell us something about how we should be modeling these processes in the future. It would be worth trying to distill for readers what we have learned from this exercise. Section 4.4: We have changed the discussion and introduction part as suggested

9) It's the editor's place, not mine, to decide to what extent this is a problem, but I feel that I need to point it out: the English language writing and usage in this paper is flawed. I appreciate that writing in a second language is difficult, and that our community benefits greatly from having viewpoints from all over the world. There is no reason why the English has to be perfect. However, in this paper the writing is in many places difficult to follow. This unfortunately makes it very hard to understand what the authors are trying to say, so the impact of what could be a very interesting paper is hidden behind confusing language. Primarily these issues relate to verb tense, word choice, and sentence structure. My suggestion is that the authors use an English editing service, or find a native speaker who will carefully go over the paper. We tried to improve the English usage in new manuscript.

Line comments (not including English usage comments, please see #9 above):

18: This rationale for the study is interesting; it would also be good to mention the more "traditional" geomorphic importance of bed cover, which is that it ultimately is a control on river and landscape evolution over geologic time. Mentioned in new manuscript. Line 23 Please see #1

30: I believe the reference is Johnson and Whipple 2010. Line 54: Yes, we have changed it.

40: We should not still be in the Introduction when some of the candidate models being

tested in the paper are introduced. As noted above, please try to devote an expanded subsection to each relevant model so that the reader can tell what is actually being tested. Section 1.3 to 1.6 : Changed as suggested.

50-55: The discussion of Hodge and Hoey feels out of place. It is obviously a relevant paper, but try to state specifically why you are discussing it here. Line 73: We have added the explanation "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 and topography."

72: The same goes for the Aubert paper; relevant work, but it is not a candidate model you evaluate, so going as far as to reproduce on of their equations is a bit of a distraction for the reader. We wanted to introduce previous theoretical and numerical models that take into account sediment cover in bedrock channel. However, as you point out, some models were evaluated and some models were not evaluated, which was difficult to understand. In new text, we widely introduce previous models then describe the governing equations of the five models dealt with in this study.

Section heading 1.1: consider revising this header to better clarify what you mean Changed as per suggestion.

109: As discussed before, please separate the descriptions of the different models. At the very least with a new paragraph, but ideally in their own subsections where you can more thoroughly discuss how the models work and the predictions that each model makes. Changed accordingly.

156/160: If the mortar is non-erodible, how can the bed be protected from "further erosion?" Line 234: The channel bed consisted of hard mortar.

Table 1: I don't remember seeing the Froude number defined anywhere. This could be done in a caption for table 1. Defined as suggested. (in Table 1)

171: See general comment #3; I am curious to know what the purpose is of calculating

Manning's n, and how the units are reconciled for any application of the values. Please see the response to the comment 3.

185: The wording here is confusing; rephrase for clarity Figure 5 and others: Please use the variable symbols complete with subscript, i.e. ksb instead of ksb Line 270: Changed We calculated the dimensionless shear stress τ_* (=(DS_e)/Rd), here R is the specific gravity of the submerged sediment (1.65). We defined the critical shear stress was τ_(*cb) is the weight average of τ_* using the number of displaced gravels.

Figure 6: say that the black line is the 1:1 line Done

Section 3.3: this is a compelling result, but it would be good to add a couple of sentences about what the implications of this result are for the model comparison.

As explained in Section 1.5, ηa/L affects the temporal change of the alluvial cover ratio but does not affect the alluvial cover ratio in the dynamic equilibrium state. Thus, ηa/L is not used in the model comparison in this study. However, ηa/L is widely used in previous numerical and theoretical models (Zhang et al., 2015; Inoue et al., 2014, 2016, 2017; Parker et al., 2013; Tanaka and Izumi, 2013; Nelson and Seminara, 2012) and it is not validated experimentally yet. So we investigated it.

Section 4: Am I wrong in thinking that Johnson's model needs to be calibrated before it can be compared against the data as presented on Figure 8? If so, section 4.2 should come before the description of Figure 8. We have changed it. Please see section 4.1

Figures 9 and 10: Why is the Turowski and Hodge model compared separately from the others? It's not necessarily bad, but it would be good to explicitly state why this was done. We have prepared separate figures for models without roughness (linear and exponential), roughness models and probabilistic models. Please see figures 10,11 and 12

Notation table: please provide units for all quantities Provided

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