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EDDA: integrated simulation of debris flow erosion, deposition and property changes

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We would like to thank the Editor, the two referees, and two readers for making thoughtful comments and constructive suggestions. We have carefully considered all the review comments and revised the paper to the best of our ability. Listed below please find our responses to the review comments. Both the review comments and our corresponding responses have been tabulated for ease of reference. The major changes are also highlighted in the text.

Response to Comments from the Executive Editor:

Comments	**Response by the Authors**
In my role as Executive editor of GMD, I would like to bring to your attention our Editorial: http://www.geoscientific-model-development.net/gmd_journal_white_paper.pdf http://www.geosci-model-dev.net/6/1233/2013/gmd-6-1233-2013.html This highlights some requirements of papers published in GMD, which is also available on the GMD website in the 'Manuscript Types' section: http://www.geoscientific-model-development.net/submission/manuscript_types.html In particular, please note that for your paper, the following requirements have not been met in the Discussions paper – please correct this in your revised submission to GMD. "– The paper must be accompanied by the code, or means of accessing the code, for the purpose of peer-review. If the code is normally distributed in a way which could compromise the anonymity of the referees, then the code must be made available to the editor. The referee/editor is not required to review the code in any way, but they may do so if	Thank you so much for reading our paper and making valuable suggestions for us to improve the paper. (1) The source code and the input files for the four test examples have been provided in a zipped file "Source Codes", which has been uploaded to the website along with this reply. (2) A section "Code availability" has been added at the end of the paper, instructing how to obtain the source codes and test input files. Code availability EDDA is written in FORTRAN, which can be compiled by Intel FORTRAN Compilers. The source code is enclosed as supplement files. The main subroutine is dfs.F90, which contains the numerical solution algorithm for solving the governing equations. Two input files are needed. One is edda_in.txt, which is the file for

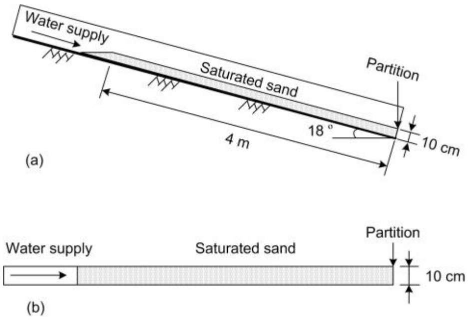
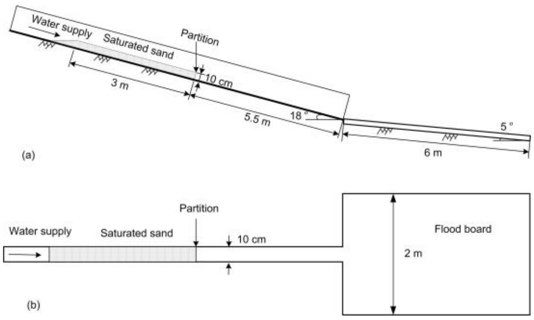
they so wish. “ “– All papers must include a section at the end of the paper entitled "Code availability". In this section, instructions for obtaining the code (e.g. from a supplement, or from a website) should be included; alternatively, contact information should be given where the code can be obtained on request, or the reasons why the code is not available should be clearly stated. ” “– All papers must include a model name and version number (or other unique identifier) in the title. ”	inputting material properties and hydrological parameters, and setting controlling options. EDDA is designed as the debris-flow simulation part of a cell-based model for analysing regional slope failures and debris flows, so the edda_in.txt file also includes the material parameters and controlling options for slope stability analysis. The other is inflow.txt, which is the inflow hydrograph file. Digital terrain data (e.g. surface elevation, slope gradient, erodible layer thickness) are included in separate ASCII grid files and enclosed in the data folder. Output files are stored in the result folder. Investigated variables at selected points are stored in EDDALog.txt. (3) A model name and version number have been included in the title “EDDA 1.0: integrated simulation of debris flow erosion, deposition and property changes”.

Response to Comments from Referee #1:

Reviewer’s Comments	**Response by the Authors**
1. The authors stress that a change in the rheology in relation to changing concentration, can be significant which may be true. However whether that plays a major role in the run-out velocity or run out distance was not clearly demonstrated in the different tests. Comparisons between measured and calculated velocities are missing. Probably sensitivity analyses with the proposed model can at least as a first step demonstrate in a theoretical way the importance of the transient rheology.	Thanks so much for the suggestions. The flume tests in Tests 3 and 4 were reported in Takahashi et al. (1992). In their work, measured flow velocity is not available. Therefore, no comparison of flow velocity is made. However, the flow discharge at the outlet of the flume and the time-varying debris fan are compared in Test 4, which reflects the comparison of flow velocities to some extent. According to the suggestion, sensitivity analyses for erosion and deposition processes have been conducted in Tests 3 and 4 (P15 L26 and P17 L20). In test 3, with the increase of coefficient of erodibility, K_e, the erosion process becomes

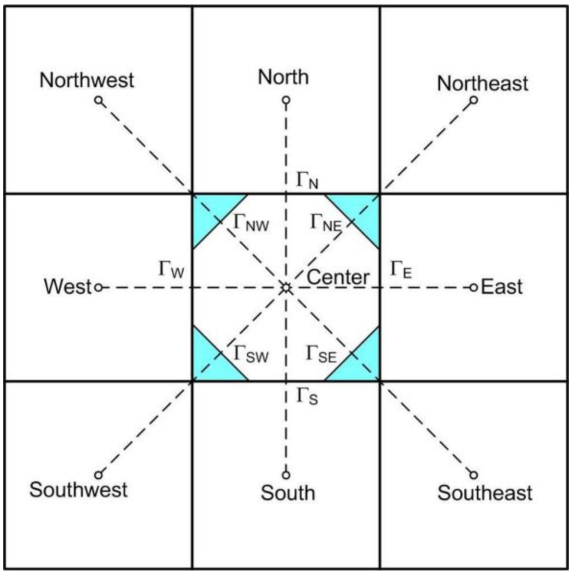
	more intensive. For example, C_v reaches 0.46 when the flow marches by only 1 m if K_e is 3.5×10^{-4} $m^3/(Ns)$; while C_v is only 0.16 when the flow marches by 4 m if K_e is 1×10^{-5} $m^3/(Ns)$. In test 4, with the increase of δ_d, the runout distance decreases while the maximum thickness of the debris fan increases significantly, and most solid materials deposit near the outlet. When the debris flow runs out of the outlet, it decelerates gradually and deposition occurs. Larger δ_d values lead to faster deposition near the outlet. With the deposition process, the amount of the moving debris flow mixture decreases, leading to decreases in the kinematic energy and potential energy, and hence the runout distance of the moving debris flow. Therefore, erosion and deposition processes significantly influence the property changes and runout characteristics of debris flow.
2. The discussion can be extended a bit. For example: how far this erosion module cover all the debris flow and entrainment processes of these debris flows: break through of landslide dams, cascading effects of dams, side wall failure by undercutting, bed failure. Also it should be mentioned that this model describes a special category of debris flows which are run-off driven. Debris flows originated from landslide failure is another category requiring a different modelling approach.	This capability of the model has been presented in Section 5 (P21 L7): "The model is suitable for describing the initiation and movement of debris flows originated from runoff-driven channel bed failure or breaching of landslide dams by overtopping erosion, which has been tested in this study. The model is also able to consider surficial material entrainment from collapses of bank material or detached landslide material as shown in the governing differential equations. But the performance has not been tested and further work is needed."
3. 7268/25 Explain these processes.	The process has been explained as follows (P2 L4): "Basal erosion, side erosion, and any other surficial material entrainment during the marching process entrain additional material into the flow."
4. 7269/14 Add also Medina et al 2008 and Quan-Luna et al 2009 who considers bed erosion as a Mohr-Coulomb failure process.	The suggestion has been well taken. The two references have been added in the introduction part (P3 L18) and the erosion and deposition part (P9 L24).

	"The Mohr-Coulomb failure process is adopted to simulate bed erosion (e.g. Medina et al., 2008; Quan Luna et al., 2012)." "Medina et al. (2008) and Quan Luna et al. (2012) consider bed erosion as a Mohr-Coulomb failure process." Medina, V., Hürlimann, M., and Bateman, A.: Application of FLATModel, a 2D finite volume code, to debris flows in the northeastern part of the Iberian Peninsula, Landslides, 5(1), 127-142, 2008. Quan Luna, B., Remaître, A., van Asch, T. W., Malet, J. P., and Van Westen, C. J.: Analysis of debris flow behavior with a one dimensional run-out model incorporating entrainment, Engineering geology, 128, 63-75, 2012.
5. 7284/13 Does the partition not disturb the entrainment process?	In experiment test, the partition may disturb the entrainment process. In the simulation, the influence of the partition on debris flow is neglected, and has been specified. "The partition and sampler are assumed to have no influence on the flow." (P15 L3) "the partition is assumed to have no influence on the flow" (P16 L7)
6. 7285 /13-29 Fig 13 How did you monitor the different phases in time of the deposition process?	The method is described in the text (P17 L4): "The flow depth, deposit thickness, debris thickness, volumetric sediment concentration, and flow velocity can be monitored for all cells. If deposition occurs somewhere, the deposit thickness there will be larger than zero. The thickness of the debris fan is the sum of the flow depth and the deposit thickness."
7. 7288/17 This is a bit strange that the Cv value at 1-1 is zero assuming no entrainment at all in the source catchment	Since Section 1-1 is upstream the main source material (Figs. 14 and 15), no erosion occurs there and Cv is hence 0.
8. 7308 Fig. 10 It is not clear how the debris flow is simulated. The figure suggests that the water "bumps" again the back side of the sediment I presume that this back side is protected by an impermeable shield and the	Thanks for the suggestion. Fig. 10 in the last version is confusing and has been revised in the revised version as follows. The sediment stretches a little bit upstream, forming a small flat area. Water is supplied upstream to

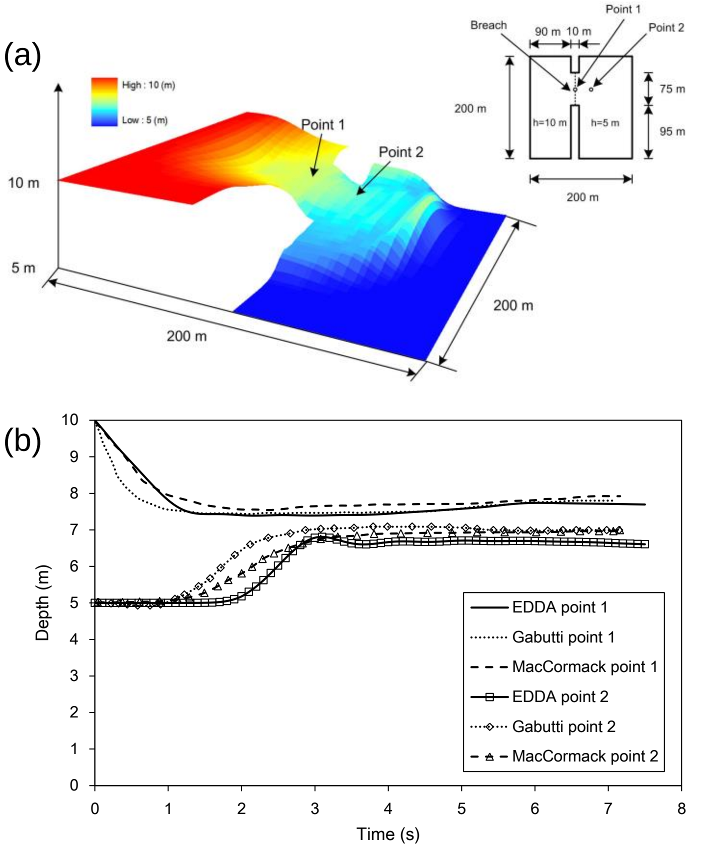
water flows over the surface of the sediment. So a bit more detail here	trigger the debris flow. 
7309 Fig 11 Same question as for Fig 10.	Fig. 11 has also been revised as follows 

<u>Response to Comments from Referee #2:</u>

Reviewer's Comments	**Response by the Authors**
1. Referring the equations (1)-(3), although they are very similar to the ones adopted by Takahashi et al., (1992) and Egashira et al., (2001), I think they are different on at least two sides. One side is the coordinate system (here is global coordinate with x-axial horizontal, while the x-axial is along the inclination of the original bed surface in the two references). The other side is originated from the way how they extend their one-dimensional mass and momentum equations to two-dimensional cases. Thus, the authors should clearly state the differences of the proposed model in this manuscript.	Thanks so much for the thoughtful suggestions. The governing equations and the expression have been revised (P5 L7): $$\frac{\partial h}{\partial t}+\frac{\partial (hv_x)}{\partial x}+\frac{\partial (hv_y)}{\partial y}=i[C_{v*}+(1-C_{v*})s_b]+A[C_{vA}+(1-C_{vA})s_A]$$ $$\frac{\partial (C_v h)}{\partial t}+\frac{\partial (C_v hv_x)}{\partial x}+\frac{\partial (C_v hv_y)}{\partial y}=iC_{v*}+AC_{vA}$$ $$\frac{\partial v_x}{\partial t}+v_x\frac{\partial v_x}{\partial x}=g\left[-\mathrm{sgn}(v_x)S_{fx}-\frac{\partial (z_b+h)}{\partial x}\right]-\frac{v_x\{i[C_{v*}+(1-C_{v*})s_b]+A[C_{vA}+(1-C_{vA})s_A]\}}{h}$$ $$\frac{\partial v_y}{\partial t}+v_y\frac{\partial v_y}{\partial y}=g\left[-\mathrm{sgn}(v_y)S_{fy}-\frac{\partial (z_b+h)}{\partial y}\right]-\frac{v_y\{i[C_{v*}+(1-C_{v*})s_b]+A[C_{vA}+(1-C_{vA})s_A]\}}{h}$$ "Similar with the two-dimensional model proposed by O'Brien et al. (1993), the governing equations above use a global coordinate system, which has been proven to simulate well flows in channels and alluvial fans (Akan and Yen, 1981; O'Brien et al., 1993). The difference is that EDDA considers changes in debris flow properties due to material entrainment and the induced momentum exchange." (P5 L22)

	The governing equations have been revised to a two-dimensional form. A volume conservation algorithm is proposed to solve the governing equations (P11 L5): "As shown in Fig. 5, each cell has eight flow directions; namely, four compass directions (i.e. north, east, south and west) and four diagonal directions (i.e. northeast, southeast, southwest and northwest). In each time step, the changes in h and C_v at each cell due to erosion or deposition are first evaluated. After that, the flow velocity, the flow discharge, and the density of the exchange flow across each flow boundary (i.e. Γ_N, Γ_E, Γ_S, Γ_W, Γ_{NE}, Γ_{SE}, Γ_{SW}, Γ_{NW}) of all the cells are computed; and the changes in h and C_v at each cell due to the flow exchange among the cells are then evaluated. The computation of the flow velocity in each of the eight directions is independent. Therefore, Eqs. (3) and (4) are reduced to one equation. This type of method has been proven to be sufficient and efficient for simulating overland flows (FLO-2D Software Inc., 2009)."  FLO-2D Software Inc.: FLO-2D reference manual, Nutrioso, Arizona, USA, 2009. O'Brien, J. S., Julien, P. Y., Fullerton, W. T.: Two-dimensional water flood and mudflow simulation, Journal of Hydraulic Engineering 119: 244-261, 1993.
2. The pattern of manifestation of the equations (1)-(3) seems flawed. The left sides of equations are one of eight directions, while the right sides are physical quantities of comprehensive directions. Such as equation (1), the left side is referred	The suggestion has been well taken. The governing equations have been revised to a two-dimensional form as shown in the last question. "As shown in Eqs. (1) and (2), the changes in h and C_v are governed by two effects; namely, erosion or deposition, and the flow exchange among cells. The

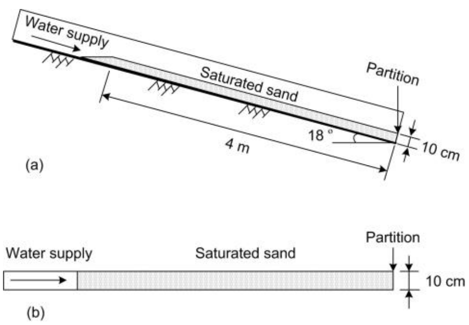
to one of eight directions, while the right side is the whole erosion or deposition depth. Thus, the authors should check these equations and write them in a proper pattern.	change in flow velocity is governed by four effects; namely, convective acceleration, flow resistance, total head, and momentum exchange due to entrainment of material or deposition." (P 10 L23) Then the method to solve the two-dimensional equations is shown as follows (P11 L5): "As shown in Fig. 5, each cell has eight flow directions; namely, four compass directions (i.e. north, east, south and west) and four diagonal directions (i.e. northeast, southeast, southwest and northwest). In each time step, the changes in h and C_v at each cell due to erosion or deposition are first evaluated. After that, the flow velocity, the flow discharge, and the density of the exchange flow across each flow boundary (i.e. Γ_N, Γ_E, Γ_S, Γ_W, Γ_{NE}, Γ_{SE}, Γ_{SW}, Γ_{NW}) of all the cells are computed; and the changes in h and C_v at each cell due to the flow exchange among the cells are then evaluated. The computation of the flow velocity in each of the eight directions is independent. Therefore, Eqs. (3) and (4) are reduced to one equation. This type of method has been proven to be sufficient and efficient for simulating overland flows (FLO-2D Software Inc., 2009)."
3. The four computational cases are not very suitable to verify the model and numerical framework. Three cases are one-dimensional. And the fourth case is also hard to evaluate the advantage of the proposed model. As the way to extend to two-dimensional framework is unique in this manuscript, I think a two-dimensional dam-break/debris flow case without and one two-dimensional dam-break/debris flow case with erosion compared with experiments or previous results is needed.	Thanks so much for the constructive suggestions. Following the suggestion, in Section 3.2, a two-dimensional dam-break water flow has been adopted to test the performance of the model in simulating two-dimensional flows (P14 L13): "A two-dimensional partial dam-breach problem reported by Fennema and Hanif Chaudhry (1987) is adopted. The sketch of the problem is shown in Fig. 8a. The computation domain is a channel 200 m in length and 200 m in width. The depth of the reservoir water is 10 m, and the depth of the tail water is 5 m. The boundary is assumed to be frictionless. The dam is assumed to fail instantaneously and the breach width is 75 m. The computation domain is discretised into a grid with cell dimensions of 2.5×2.5 m. The time step is kept at 0.01 s. The flow resistance slope, S_f, is taken as 0 in this test as the channel is assumed frictionless. The water depth at 7.1 s after the dam breaches is shown in Fig. 8(a), which agrees with the result of Fennema and Hanif Chaudhry (1987). Two points in Fig. 8(a) are selected for investigating the variation of water depth with time. The results from the numerical solution using EDDA and two numerical solutions by Fennema and Hanif Chaudhry (1987) are compared in

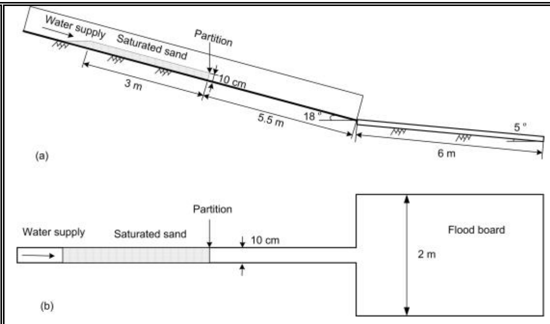
	Fig. 8(b), which again agree reasonably well. "  In Tests 3 and 4, a very small grid size of 0.02×0.02 m is adopted since the width of the flume is only 0.1 m. The two numerical tests are now two dimensional. The model also performs well in these two tests.
4. The Introduction should be strengthened and more attention should be paid to the advances of depth-integrated model involving erosion/deposition and associated rheology model. The following references (even more) associated erosion effects should be included in Instruction.	The suggestion has been well taken. The advances of depth-integrated models involving erosion/deposition and associated rheological models have been reviewed in depth in the introduction part (P3 L16): "Depth-integrated models have been widely adopted to describe erosion and deposition (e.g. Takahashi et al., 1992; McDougall and Hungr, 2005; Armanini et al., 2009; Hungr and McDougall, 2009; Iverson et al., 2011; Quan Luna et al., 2012; Ouyang et al., 2014). The Mohr-Coulomb failure process was adopted to simulate bed erosion (e.g. Medina et al., 2008; Quan Luna et al., 2012). Ouyang et al. (2014) further combined the Mohr-Coulomb model and the Voellmy model to overcome the flaws of each of these two models. The changes in flow depth, flow velocity and debris mass have been accounted for in the literature. Limited attempt has also been made to consider the evolution of volumetric sediment concentration (Takahashi et al., 1992; Denlinger and Iverson, 2001;

<table>
<tr><td></td><td>Ghilardi et al., 2001). Several key problems, however, still remain. How can one describe the various phases of a debris flow (e.g. clear water flow, hyper-concentrated flow, and fully developed debris flow) using a general rheological model? How do the properties of debris flows (e.g. volumetric sediment concentration, yield stress, viscosity) change in the erosion and deposition processes? How do these changes affect the runout characteristics of the debris flow? ”</td></tr>
<tr><td>5. 7273/1-5, simulution should be modified to be simulation.</td><td>The word has been corrected.</td></tr>
<tr><td>6. 7280/1-5, the equations (29) and (30) seems to have some clerical mistakes.</td><td>The two equations have been revised (P12 L6).

$$h_{new} = h_{predi} + \frac{\sum_{b=1}^{nb}(q_b \Delta t)}{A_{cell}}$$

$$\rho_{new} = \frac{\rho_{predi} h_{predi} A_{cell} + \sum_{b=1}^{nb}(\rho_b q_b \Delta t)}{h_{new} A_{cell}}$$

where h_{new} and ρ_{new} are the updated flow depth and density, respectively; q_b and ρ_b are the discharge and density of the exchange flow across a boundary, respectively; *nb* is the number of flow boundaries of the cell (i.e. eight); A_{cell} is the area of the cell.</td></tr>
<tr><td>7. In Figure 10 and 11, the description of sediment part is bad and need redraw.</td><td>The two figures have been revised as follows.

</td></tr>
</table>

	
8. 7314/figure 16, Time(h) or Time(t)??	It has been revised to Time (hour).

<u>Response to Comments from M. Peng:</u>

Reviewer's Comments	**Response by the Authors**
1. The model combined many empirical equations, like Eq. (21) from Takahashi et al. (1992), Eq. (32) from Chang et al. (2011) and so on. However, most of the empirical equations have their limitation due to incomplete or local data sets. Thus, the application of each empirical equation may bring some degree of uncertainty. The combination of so many empirical equations, however, may bring an amount of uncertainties. For example, The Ke in Equation (32) is very sensitive to the parameter of void ratio. While the debris flow in real case varies largely in void ratio.	Thanks so much for the comments. The limitations of the empirical equations have been specified in Section 5 (P21 L20). Sensitivity analyses for erosion and deposition have been conducted to investigate the uncertainties to a certain extent. For a specific area, detailed field tests and laboratory tests can be conducted to obtain soil properties and hydrological parameters, which can reduce the uncertainties to certain extent. The investigation of the model and parameter uncertainties in debris flow analysis is beyond the scope of the paper.
2. The debris flow may not flow to only one of the eight directions in real case. Some may flow to two or more directions at the same time. Errors may increase when the cells become larger, for example, the Xiaojiagou case with limited number of cells.	In EDDA, a debris flow is allowed to flow to all the eight directions at the same time. It is right that a smaller cell size leads to more accurate results. The computational time is longer of course.
3. Is that model able to consider landslide dam breach with variety of soil particles? For instance, the dams with both large particles (rocks) and small particles.	The grain size distribution of material highly influences the soil properties such as friction angle, cohesion, critical erosive shear stress, coefficient of erodibility and so on. In a sophisticated analysis, detailed tests are required to get the soil properties at different locations. Based on this, soil properties are

	assigned to all the cells. The variability at different depth can also be incorporated. If all the work is well done, the model is able to consider the breaching of landslide dams of a range of soil particles.

Response to Comments from S. Jiang:

Reviewer's Comments	**Response by the Authors**
1. The key is that the numerical model developed in this paper should be made more transparent such that it can be easily accessible to general readers.	Thanks for the suggestion. The source code of EDDA has been enclosed in the supplement files, which will be open to the readers through Geoscientific Model Development.