Simulation of the Motion of Semi-Coherent Landslides

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ABSTRACT

Reliable methods that are able to predict key characteristics of landslide runout are essential in analysing the risk posed by extremely rapid landslides. Runout models derived based on fluid mechanics have been successful in simulating extremely rapid flow-like landslides, however these models are unable to simulate extremely rapid coherent landslides or slides that are initially coherent and then turn flow-like. This paper presents a model based on solid mechanics that is able to simulate extremely rapid coherent landslides. Its features include: (*i*) the ability to simulate both translation and rotation of an arbitrarily shaped sliding mass across complex three dimensional terrain, (*ii*) the ability to simulate landslides that are initially coherent and then turn flow-like and (*iii*) simplicity of use and computational efficiency. The model has been verified by simulating solid mechanics problems for which analytical solutions exists. It is able to accurately predict both velocities and displacements of these systems. The results of the back analysis of the Goldau Rock Avalanche is presented. This analysis shows that the combined solid mechanics-fluid dynamics model is able reproduce the bulk properties of this complex sliding and flow event.

RÉSUMÉ

Il est primordial d’établir des méthodes fiables afin de prévoir les principales caractéristiques des distances d’éboulement au cours d’un glissement de terrain lorsqu’on analyse le risque posé par les glissements de terrain extrêmement rapides. On est parvenu à simuler des glissements de terrain de type liquide extrêmement rapides grâce à des modèles d’éboulement fondés sur la mécanique des fluides, cependant ces modèles ne parviennent ni à simuler des glissements de terrain cohérents extrêmement rapides, ni des glissements de terrain initialement cohérents, qui ensuite se fluidifient. Cette dissertation présente un modèle dérivé sur la base de la mécanique des solides qui est capable de simuler des glissements de terrain cohérents extrêmement rapides.

Ses caractéristiques comprennent: (i) la capacité à simuler à la fois la translation et la rotation d'une masse de glissement de forme arbitraire sur un terrain en trois dimensions complexes, (ii) la capacité à simuler des glissements de terrain qui sont initialement cohérents et qui ensuite se fluidifient et (iii) la simplicité de l'utilisation et l'efficacité de calcul. Le modèle a été vérifié en simulant des problèmes de mécanique des solides pour lesquels des solutions analytiques existent déjà. Il est capable de prédire avec précision les vitesses et les déplacements de ces systèmes. Les résultats de l'analyse de fond sur l’Avalanche de Goldau Rock seront pris en compte. Cette analyse démontre qu’un modèle combiné de dynamique de la mécanique des fluides appliqué à des éléments solides est capable de reproduire l’essentiel des propriétés de ce type d’événement de glissement complexe.

1 INTRODUCTION

Rock and debris slides and avalanches are extremely rapid landslides that can cause a large amount of damage far from the source area. Prediction of the areas that will be affected by these events, as well as the velocity and deposit depth of the events are an important part of determining the risk posed by these types of landslides. A commonly observed characteristic of the motion of these landslides is that they are initially coherent before fragmenting and becoming flow-like. Current dynamic models, which are commonly based on fluid mechanics, are unable to take into account the initial "rigid" phase of motion, resulting in an over prediction of the lateral spreading of the landslide.

2 PREVIOUS WORK

Landslide runout models can be classified as either empirical or analytical depending on whether the model is based on data correlations or on underlying physical relationships. A review of runout prediction models is provided by Hungr et al. 2005. Of particular interest to this article are the semi- empirical equivalent fluid models. The initial framework for these models was proposed by Savage and Hutter (SH) in 1989. The SH model assumes that the body of the landslide is in a state of a fully-developed and distributed frictional deformation, controlled by an internal friction angle. A zero value of this angle implies hydrostatic fluid conditions. In the Savage & Hutter 1989 model, the basal sliding occurred at a frictional interface, with a lower ("basal") friction angle. Hungr (1995) extended the model by allowing other, non-frictional rheologies to apply on the sliding base. The Hungr (1995) model was extended into three dimensions by McDougall & Hungr 2004 and implemented in a model called DAN3D. The model presented in this article is an addition to DAN3D (Mcdougall 2006), and a brief description of that model is provided.

DAN3D is a depth averaged Lagrangian implementation of the SH model, able to simulate landslide motion across complex 3D terrain (McDougall & Hungr 2004). The solution method used by DAN3D is smooth particle hydrodynamics (Monaghan 1992), a continuum meshless Lagrangian method that allows for large strains and bifurcations of the moving mass.

In the equivalent fluid approach it is assumed that heterogeneous and complex sliding material is replaced by a mass of hypothetical fluid governed by simple internal and basal rheologies. The rheological parameters are selected by trial and error inverse analysis of cases similar to the case of interest. Due to this use of “trial and error” inverse analysis, the model is semi-empirical (McDougall & Hungr 2004). DAN3D has been used to successfully model a number of cases including Zymoetz River (McDougall et al. 2006) and the Frank Slide (McDougall & Hungr 2004). For a detailed description of the derivation and assumptions of DAN3D the reader is referred to McDougall & Hungr (2004). An overview of the entrainment algorithm is provided in Mcdougall & Hungr (2005). For an overview of both DANW and DAN3D the reader is referred to Hungr & McDougall (2009).

The key premise of the SH method is that the fluid mass is generated from the source volume instantly at the point of detachment. In reality, however, many natural landslides initiate by the sliding motion of a mass of rock or soil, which is initially fully or partly coherent. The initial block only gradually disintegrates and assumes the character of a frictional fluid, as assumed by the SH model. As a result, analyses of natural rock avalanches with the DAN3D model, for example, often predict excessive lateral spreading of the thick initial mass in the vicinity of the source area.

3 OBJECTIVES FOR MODEL DEVELOPMENT

It is common for rock avalanches to originate from rock slides, but the physics governing the motion of these two types of landslides are different. Rock slides involve the movement of a coherent mass on a basal sliding plane, although they can require some internal distortion in order for movement to be kinematically feasible. The motion of these landslides is best captured using solutions derived from solid mechanics. Once fragmentation is completed, the subsequent motion of rock avalanches involves the flow-like motion of fragmented rock (Hungr et al. 2013). This failure type can be captured using fluid mechanics in the framework of the SH model.

Many researchers who have applied Dan3D to rock avalanche case studies have noted that the assumption of instant fluidisation leads to excessive lateral spreading of the sliding mass (Chalindar 2005), (Fitze 2010), (Mcdougall 2006). This limitation restricts the use of Dan3D to cases where the sliding mass fluidizes soon after initiation. The addition of a solid mechanics solution allows Dan3D to simulate initially rigid rock avalanches, making it applicable to the hazard analysis of a wider variety of case histories. A good example of a rock avalanche that exhibited this combination of rigid and fluid behaviour is the North Nahanni Slide (Wetmiller et al. 1987). A photo of this rock avalanche can be seen in Figure 1. A large coherent block can be observed on the sliding surface with still intact vegetation. The dynamics of this type of movement cannot be easily described with fluid mechanics. The solid mechanics solution presented here allows this type of event to be simulated.

The objective of this work is to introduce a solid mechanics solution into DAN3D. This will allow for the simulation of the initial phase of motion during rock avalanches while the failed mass moves as a slide, before it fragments and turns flow like. The requirements of the model are to:

1. Simulate the translation and rotation of an arbitrarily shaped sliding body as it moves across complex 3D terrain
2. Simulate landslides that are initially coherent and then turn flow-like
3. Facilitate the back analysis process through simplicity of use and computational efficiency

Rotation as well as translation is important in the motion of coherent slides, as demonstrated in the Vajont compound slide (Superchi 2012), the Mt. Granier rock avalanche (Hungr et al. 2013) and the Mystery Creek rock avalanche (Nichol et al. 2002). The model must be able to determine slide characteristics based on solid mechanics, and then allow for transition to a fluid mechanics solution during the simulation. This is necessary for the simulation of all phases of movement for many rock avalanches, such as the Goldau rock avalanche (Fitze 2010). Simplicity of use and computational efficiency are necessary due to the semi-empirical framework to which the DAN models subscribe. The model parameters are determined through back analysis, and making forward predictions with the model can only be done once a large dataset of back analysed parameters exists. It is important that the model facilitates this extensive back analysis process.

4 MODEL DERIVATION

The model is derived using an approach similar to 3-D limit equilibrium. Instead of solving for a factor of safety, the solution algorithm determines the unbalanced force and moment acting on the sliding body, which is then used to determine translational and rotational accelerations. The accelerations are then integrated to determine translational and rotational velocities and displacements.

5 MODEL ASSUMPTIONS

In the following derivation the sliding mass is discretized into an assembly of connected columns. The columns are rectangular and all have the same basal area. A Cartesian coordinate system is used, and the Z axis is the vertical axis. The model makes the following assumptions about the sliding mass, which are considered to be justified on the assumption that the thickness of the sliding body is much less than its lateral extent and that the strength of the geomaterials is greater in compression than in shear:

Figure 1: North Nahanni Rock Avalanche. A large coherent block can be seen on the rupture surface near the centre of the photo, indicating a phase of coherent motion during the event. Photo: O. Hungr.

1) The bases of the columns are in a state of fully-developed shear failure so that normal and shear stresses on the surface can be related with a user-specified basal rheology.
2) The sliding mass behaves as a flexible block, able to deform in the Z direction but prevented from deforming in the X and Y directions. In other words, differential movement of columns is permitted in the vertical direction but not in the horizontal plane. This differential movement is required to ensure that the sliding mass remains on the sliding surface.
3) The sliding mass is assumed to have small height, compared to its length. This assumption is analogous to the shallow flow assumption used to derive many runout models based on fluid mechanics. The implication of this assumption is that moments about the horizontal (X and Y) axis can be ignored.
4) For the current formulation it is assumed that inter-column shear forces can be neglected. This is the same assumption as is made in simplified limit equilibrium formulations.
5) It is assumed that the weight vector of each column is applied at the centre of the column.
6) It is assumed that the basal shear resistance vector of each column is applied where the column intersects the sliding surface in the middle of the column.
7) It is assumed that the sliding mass moves only through rotation and translation. As such the model is not applicable to sliding events, such as rockfalls, that have some components of free fall, rolling and toppling.

6 GOVERNING EQUATIONS

Based on the assumptions detailed above the following system of equations describe the translation and rotation of a flexible block over three dimensional terrain:

$$m_{body} * \dot{v}_x = F_x \qquad [1]$$

$$m_{body} * \dot{v}_y = F_y \qquad [2]$$

$$I_z * \dot{\omega}_z = T_z \qquad [3]$$

Where m_{body} is the mass of the sliding body, $(\dot{v}_x, \dot{v}_y)$ are the translational accelerations of the body, (F_x, F_y) are the components of the unbalanced force acting on the body, (I_z) is the moment of inertia about the vertical axis, $(\dot{\omega}_z)$ is the angular acceleration of the body about the vertical axes and (T_z) is the external torque acting on the body.

The system of equations derived above is solved using the method of columns. When the method of columns is used the total force and torque acting on the flexible block is the sum of the individual forces and torques acting on the columns.

Since internal forces are balanced within the moving body the individual net forces $(F_{x,i}, F_{y,i})$ acting on each column which contribute to the unbalanced force of the sliding mass are (Figure 2):

$$F_{x,i} = G_{x,i} - F_{x_{basal,i}} \qquad [\,4\,]$$

$$F_{y,i} = G_{y,i} - F_{y_{basal,i}} \qquad [\,5\,]$$

Where the subscript *i* represents an individual column, F_i is the total force acting on the ith column, G is the downslope component of gravity and F_{basal} is the basal resistance force which acts in the direction of motion.

The torque exerted by an individual column about a vertical axis passing through the centre of mass of the body can be expressed as:

$$T_{z,i} = \left(G_{y,i} - F_{y_{basal,i}}\right) * x_i' - \left(G_{x,i} - F_{x_{basal,i}}\right) * y_i' \qquad [\,6\,]$$

Where x' and y' are the x and y coordinates of the column relative to the centre of mass of the moving body and the subscript i denotes an individual column.

The total force and total torque on the column assembly can be determined by summing the individual forces and torques on each column. Once the total force and torque is known the translational and rotational accelerations can be determined with equations 1,2 and 3. These are then numerically integrated to determine velocities and displacements.

The equations derived in the previous section describe the movement of flexible block through time over three-dimensional terrain. This model has been integrated into DAN3D to allow it to simulate cohesive slides as well as slides that are initially cohesive and then become flow-like. The fluidization routine assumes that the sliding mass fluidizes in a single timestep and initial particle velocities are calculated based on the final column velocities.

7 MODEL VERIFICATION

In order to verify the implementation of the model, two analyses were conducted. These analyses verify both the translational and rotational components of the motion, and were completed by comparing model predictions to analytical solutions. The two problems selected are a block sliding down an inclined plane and a rod rotating about a fixed end.

The configuration of the block sliding down the inclined plane is shown in Figure 3. The block is initially at the top of the ramp and then slides down parallel to the x-axis as time progresses. Displacements are measured in the x direction at one second time intervals.

The configuration of the rod rotating about a fixed end is shown in Figure 4. The code was modified so that rotation occurs about the fixed end of the rod (as opposed to the centre of mass), and a constant force in the positive y direction was applied to the column with (initially) the largest x coordinate. The rod then rotates about the fixed end in a manner similar to a pendulum as the force remains constant in both magnitude and direction.

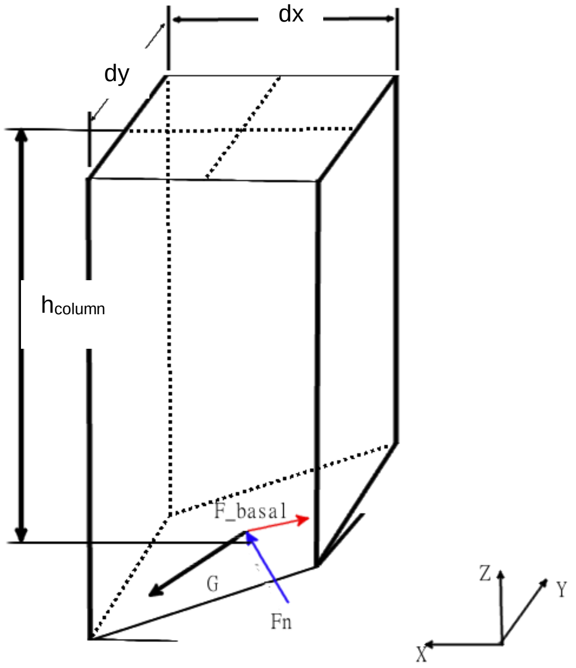

Figure 2: Forces acting on a column when internal strength is neglected. G denotes the downslope component of gravity, Fn the component of gravity normal to the slope and F_basal is the resistance force. Note Fn (blue) is used to calculate F_basal. F_basal is not collinear with G as it acts in the direction of motion.

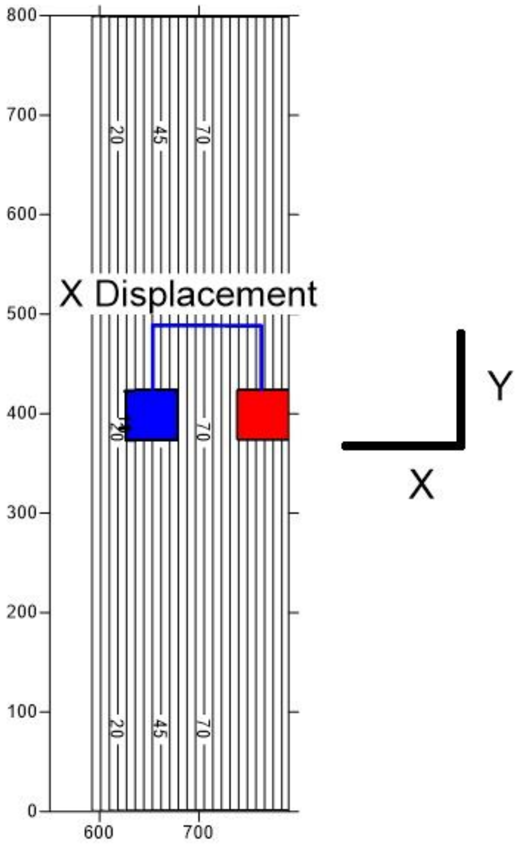

Figure 3: Overhead view of the simulations that verify the translation algorithm. The block is shown in its initial configuration (red) and in its position after 9 seconds (blue). The X displacement (plotted in Figure 5 for various times) is marked with the blue line.

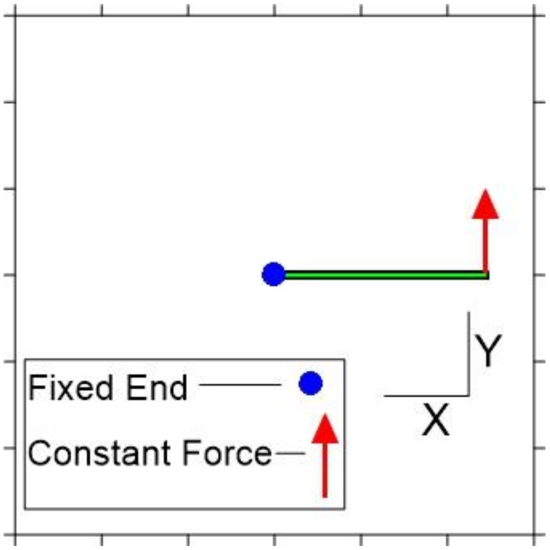

Figure 4: Test configuration for the verification of the rotation algorithm. The end is pinned and a constant force is applied in the y direction. The rod rotates about the pinned end in a manner similar to a pendulum.

The results of these simulations are summarized in Figure 5 and Figure 6. There is good agreement between the simulated and analytical predictions for both problems. The slight differences between the simulated and analytical results are likely due to discretization errors. These cases show that the model is able to accurately solve the governing equations, and confirm that all quantities (such as moment of inertia) are calculated accurately.

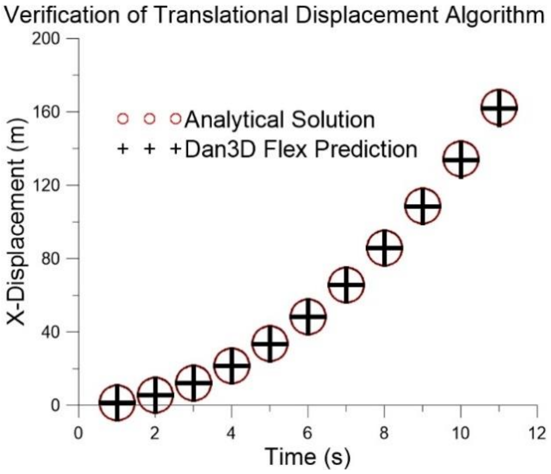

Figure 5: Comparison of predicted x - displacements by the analytical solution and Dan3D flex

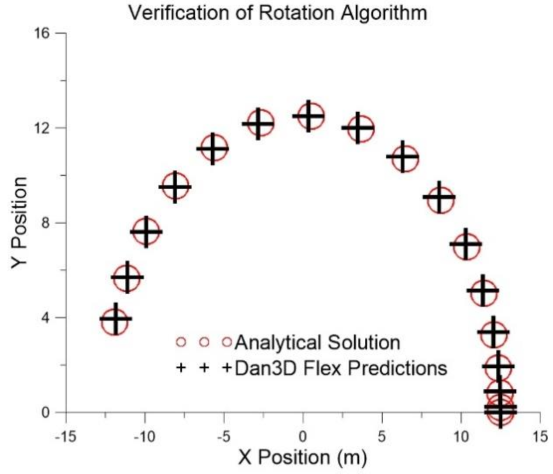

Figure 6: Comparison of centre of mass location predicted by the analytical solution and Dan3D flex at various times

8 BACK ANALYSES

The inverse analysis of the Goldau rock avalanches is provided in the following sections. It is not the intent of this paper to provide detailed case history of this landslide. This case is used to demonstrate the excessive lateral spreading predicted by the fluid dynamics solution, and show that the current model solves this problem. The Goldau Rock Avalanche initiated as planar failure, so it is unlikely that it underwent significant internal deformation.

9 GOLDAU ROCK AVALANCHE

The Goldau Rock Avalanche was a tragic landslide that occurred in Switzerland in 1806. This event involved the detachment of 35-40 x10^6 m^3 of material that travelled several kilometers. The landslide claimed 457 lives, destroyed 111 houses and initiated a 20 m high wave in Lake Luarez, located in the deposition area (Fitze 2010). Berner (2004) provides a detailed overview of site geology and future hazard potential. Thuro et al. (2006) provides a numerical analysis of the failure mechanism of the landslide. The simulations detailed here build on a previous DAN3D analysis performed by Fitze (2010). The topography files and simulation constraints are the same as those used in that analysis. A photo of the source area is shown in Figure 7.

9.1 Fully Fluid Simulations

The results of the fully fluid simulation are shown in Figure 8. The fully fluid simulations predict too much spreading of the sliding material during the early stages of the event. This results in an over prediction of the landslide trimline.

9.2 Initially Rigid Simulations

The results of the simulations where the sliding mass is assumed to initially behave as a flexible block are shown in Figure 9. The trimline and deposit distribution are well simulated.

10 CONCLUSIONS

The model presented here expands the functionality of DAN3D to allow it to simulate the initially rigid motion of some rock avalanches. This model has a number of unique features, including the ability to account for both translation and rotation of the sliding mass as it moves across three dimensional terrain. The model can transition from the solid mechanics solution to the fluid mechanics solution, allowing for the disintegration of the sliding mass to be simulated. The model only requires one additional parameter, and is computationally efficient. Both these features make the new model amenable to inverse analyses.

The flexible block model has been verified against both analytical solutions, as well as one full scale rock avalanche. The model performed well in all cases, demonstrating that the flexible block model is able to accurately reproduce the bulk characteristics of the coherent phase of rock avalanches. A fully calibrated model would be able to provide predictions of velocity and deposit depth of these events.

The methodology underpinning DanW and Dan3D is semi-empirical. In order to use these models for forward analyses a database of calibrated model parameters, based on successful inverse analyses, must be established. For these inverse analyses to provide accurate parameters for forward analyses they must follow, as closely as possible, the physics that govern the landslide movement. During the initial movement phase of many rock avalanche the behaviour of the sliding mass is governed by solid mechanics, not fluid mechanics.

Being able to accurately simulate this initial phase leads to more realistic calibration and more accurate forward analyses for these types of events.

Figure 7: Photo of the Goldau source area

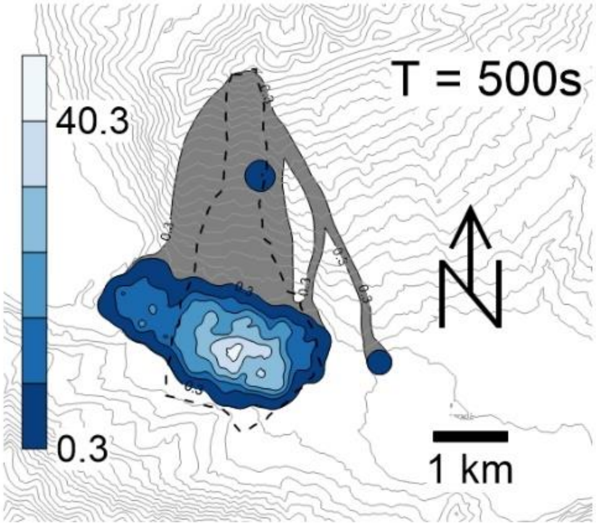

Figure 8: Final deposit shape and trimline of fully fluid simulation. Dashed line shows true trimline and the grey area is the predicted trimline.

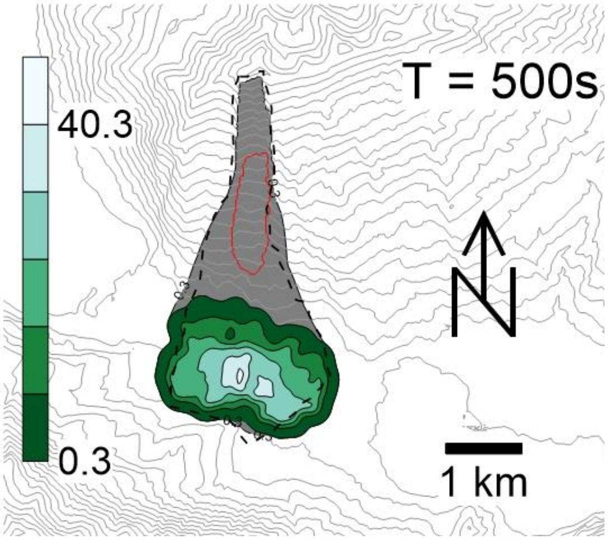

Figure 9: Final deposit shape predicted by Dan3D Flex. The red outline shows where the sliding mass is fluidized.

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