Tamotsu Takahashi

# Debris Flow

## Mechanics, Prediction and Countermeasures

CRC Press
Taylor & Francis Group
A BALKEMA BOOK

2nd edition

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CRC Press
Taylor & Francis Group
Boca Raton London New York Leiden

CRC Press is an imprint of the
Taylor & Francis Group, an **informa** business

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Typeset by MPS Limited, Chennai, India
Printed and Bound by CPI Group (UK) Ltd, Croydon, CR0 4YY



*Library of Congress Cataloging-in-Publication Data*

Takahashi, Tamotsu, 1939–
[Dosekiryu no kiko to taisaku. English]
Debris flow : mechanics, prediction and countermeasures / Tamotsu Takahashi. — 2nd edition.
pages cm
Includes bibliographical references and index.
ISBN 978-1-138-00007-0 (hardback : alk. paper) — ISBN 978-0-203-57674-8 (eBook PDF)
1. Debris avalanches. 2. Rock mechanics. I. Title.
QE599.A1T3513 2014
551.3′07—dc23

2013050615

Published by: CRC Press/Balkema
P.O. Box 11320, 2301 EH Leiden, The Netherlands
e-mail: Pub.NL@taylorandfrancis.com
www.crcpress.com – www.taylorandfrancis.com

ISBN: 978-1-138-00007-0 (Hbk)
ISBN: 978-0-203-57674-8 (eBook PDF)

# Preface

A typical debris flow is a torrential flow of a mixture of water, mud and debris that suddenly pushes ahead with a vanguard of huge, jostling and roaring boulders. It is certainly a very fearful phenomenon that causes disasters, but it is also truly a wonder of nature exciting the curiosity of researchers as to how such a phenomenon can arise. The phenomena themselves had been recognized since ancient times in Japan and given various mnemonic names to make people aware of the dangers. Although there were several detailed witness records around in 1965 when I began working for the Disaster Prevention Research Institute of Kyoto University (hereafter called DPRI), the characteristics and mechanisms of debris flows were still vague, and it was called a 'phantasmal disaster'.

My first field investigation of such disasters was the 'Okuetsu torrential rain disaster' in 1965, which was brought about by a locally concentrated rainfall at the boundary between Fukui and Gifu Prefectures in central Japan. I found many wooden houses were buried up to the second floor by debris that consisted of particles a few tens of centimeters in diameter that had run down the mountain at the back of the town. Yet the frames of those houses were not completely destroyed. This fact told us that the thick deposit of big stones was laid gently. I wondered how such a phenomenon could occur.

In 1968, a debris flow occurred in the Shiramizudani experimental watershed of Hodaka Sedimentation Observatory, DPRI. I was greatly impressed by the traces of debris flow; it passed through a shallow and narrow stream channel incised in the wide riverbed leaving almost no large boulders in the central part, whereas along both sides of the channel big boulders were left in an orderly fashion as if they were artificially arranged levees. I wondered why such a phenomenon occurred.

The same rain storm that generated the Shiramizudani debris flow caused the 'Bus tumbling down accident at the Hida River'. Two buses among the queue of vehicles obliged to stop by a landslide ahead were attacked by a debris flow from the side, and the buses with a total of 104 victims on board tumbled into the Hida River that was parallel to the road. This accident clearly showed the dangerous situation of the mountain road, and it triggered the subsequent reinforcement of those roads by the governments. I felt keenly that the prediction of debris flow occurrence to help early refuge was an urgent theme to be investigated.

A similar accident happened in 1971 at Aioi, Hyogo Prefecture, Japan. In this case, a bus was pushed down to the valley bottom from the hillside road by a small-scale landslide. The facts I paid attention to in this case were that grasses on the route of earth block's motion survived although they were leveled down to the ground, and the surface of the road pavement on which the bus traveled was not much damaged. These facts revealed that the landslide in this case had little ability to erode the ground, yet it had the power to push away a bus. A month later, a debris flow occurred in a small ravine in Shodo Island. Our main object of investigation was to make clear whether the collapse of the road embankment at the headwater triggered the debris flow or whether the debris flow that was generated by the erosion of the riverbed just downstream of the road caused the collapse of the embankment. Setting our conclusion to this question aside, I would like to mention that the upstream part of the ravine was completely eroded to the bedrock. These two examples at Aioi and Shodo Island show that some debris flows have enormous ability to erode the ground but others do not. What is the cause of the difference between the two?

As described above, through the field investigations, I was much interested by the phenomena of debris flow, which had been little studied, so little was known about the mechanism of occurrence, flowage and deposition of debris flow. Thus, I made a resolution to investigate debris flow. I was, however, at that time involved mainly in research on the characteristics of flood flow in river. Therefore, my fully-fledged debris flow research commenced after 1975.

Because my main interest was the curious behaviors of debris flow, I commenced my work with the aim of making clear the physical mechanisms of debris flow phenomena. Then, being a staff member of DPRI, I developed my work on the engineering subjects such as the prediction of hazards and the functions of various structural countermeasures. The decision of specific themes was also influenced by the needs of the times; it was in line with the change of governmental policy against riverine hazards. In Japan, the imbalance between the property increment due to urban development and the necessary investment for river conservancy to cope with the enhanced vulnerability became larger and larger after the mid-1960s and the urban flood hazard problems became serious. A governmental program named 'comprehensive mitigation measures against flood damage' was launched in 1977. This program placed emphasis on the non-structural (in other words, soft) countermeasures in addition to the structural (in other words, hard) countermeasures as an effective strategy. As a part of the program, the policy to cope with debris flow disasters by evacuation was put forth. The designation of debris flow prone ravines was essential for the implementation of the plan, and the method to identify the potential debris flow ravines proposed by us was adopted. Since then, I have made a strong effort to research both the fundamental mechanics and rather practical problems such as the delineation of hazardous area, the determination of the critical rainfall for evacuation, etc.

The background of the importance of research on the mitigation of sediment disasters is as follows. In Japan, the number of casualties due to water related disasters has experienced a big change from more than 2,000 per annum in the decade after 1945 to less than 50 per annum in recent years. The improvement of major rivers has lessened large-scale flooding and it has surely contributed to the decrease in the number of casualties, but the improvement of minor rivers lags behind and the development of slope land makes the situation worse for the vulnerability to sediment hazards. Namely, among 5,666 casualties due to water related hazards in the 31 years from 1967 to 1997, 29% are due to cliff failures and 25% to debris flows or comparatively large-scale landslides. The tendency that the majority of casualties are due to sediment hazards has become especially conspicuous recently. For example, in the case of the 'Nagasaki disaster' in 1982, 75% of the total 299 casualties and in the 'San-in disaster' in 1983, 90% of the total of 121 casualties were due to sediment hazards. More recently, almost all the remarkable disasters such as the 'Gamaharazawa debris flow disaster' in 1996 (14 people killed); the 'Harihara River debris flow disaster' in 1997 (21 people killed); the 'Hiroshima disaster' in 1999 (24 people killed); and the 'Minamata debris flow disaster' in 2003 (19 people killed) were sediment hazards.

This situation might be considered as inevitable under Japanese natural and social conditions. At present, 289,739 cliff-failure-prone steep slopes, 11,288 slowly and largely moving landslide-prone slopes, and 103,863 debris flow-prone ravines are designated. These designations are under the criterion that more than five families or some kinds of public facilities such as a school and administrative institution exist inside the possible hazardous area. Taking the debris flow-prone areas as example, the number of designated areas increased year by year: in 1977 (the first designation) there were 62,272; in 1986, 70,434; in 1993, 79,318; and in 2002, 89,518. This increment is partly due to the reassessment of the survey, but it is mainly due to the encroachment of inhabitants into potential hazardous areas.

The necessity of development regulation in potentially hazardous areas had been pointed out long before, but no laws to put the regulation into effect existed, so that it had been free to develop. With the 'Hiroshima disaster' as a turning point, the 'sediment disaster prevention act' has been enforced since May, 2000. In the possibly extremely hazardous areas designated by this act, all the organized housing land development and personal house buildings that do not have adequate strength to resist sediment hazards are prohibited, and the local government can advise the inhabitants already inside that area to move to a safer area.

In parallel with the implementation of this act, the designation of hazardous areas has been reassessed. Namely, areas designated so far are defined as category I, and the newly designated hazardous areas of category II and III are added. In category II areas fewer than five houses exist, and in category III areas no houses exist at present, but if houses were constructed, they may well meet with disasters. The total of category II and III ravines with possible debris flows was 94,345 in 2002. These numbers of Categories I to III are of course too many to be adequately treated by the structural countermeasures, hence, soft countermeasures such as the control of development and evacuation in advance are important. This is the reason why the sediment disaster prevention act is enforced.

Because the execution of the sediment disaster prevention act attaints the usage of personal properties, the delineation of hazardous areas must be accurate and with substantial reasons. The state of the art of debris flow engineering may partly meet the demand, but it is still far from reliable. Researchers are responsible for the improvement of reliability.

The importance of sediment hazards is not limited to Japan. There are many countries exposed to even worse conditions. In China, more than a hundred prefectures and cities suffer from debris flow disasters every year, and more than a hundred people are killed and more than two billion yuan are lost. As an example, in the disasters of 2002, 1,795 people died due to water-related hazards and among them 921 were due to sediment hazards like debris flows. In Colombia in 1985, more than twenty thousand people were killed by the lahars generated by the eruption of Nevado del

Ruiz volcano and Armero City disappeared. In Venezuela in 1999, the Caribbean cities were attacked by large-scale debris flows and more than twenty thousand people were killed. In Taiwan in 2001, a rainstorm associated with a typhoon generated many debris flows and killed 214 people. Many debris flow disasters also occur in other countries such as Nepal, Indonesia, the Philippines, Italy, Switzerland and France. Therefore, the improvement of debris flow research can contribute globally.

This book, at first, describes the various characteristics of debris flows and explains that debris flows can be classified into several types. Then, the mechanics of the respective debris flows are explained and in the process of discussion the advantages and drawbacks of various previous theories will be made clear. After that, the processes of occurrence and development, the characteristics of fully developed flow and the processes of deposition are explained from the mechanical point of view. Up to Chapter 5, discussions are concerned with fundamental mechanical theories; the rest of the book is concerned with the application of these theories. Namely, in chapter 7, there are computer simulations of some actual disasters for which we participated in the field investigations. The last chapter selects some debris flow controlling structures and discusses their effectiveness and performance designs, and it also discusses the soft countermeasure problems such as the identification of debris flow prone ravines and the prediction of occurrence by the concept of precipitation threshold.

My standpoint throughout the book is the fundamental quantitative explanation of the phenomena, and the design of structural countermeasures. The performances are discussed based on the fundamental mechanics, putting the empirical method out of the way as far as possible. As a consequence, many mathematical formulae appear, and I am afraid this makes the book daunting. But, even if readers ignore the complicated formulae, they will be able to understand the physical phenomena of debris flows as well as the current status and future needs of research.

This book does not aim to review the existing investigations thoroughly, but it intends to offer an overview of my works. Therefore, previous very important contributions might not be referred to. It is not due to disrespect but to make my thought clearer. Pyroclastic flows and snow avalanches are referred to as the phenomena similar to debris flow in Chapter 1, but in this book, due to the limitation of pages and in view of coordination as a book, I omitted detailed descriptions of these phenomena. I would like to discuss these problems on another occasion.

This book is published under my sole name, but the majority of the investigations referred to in this book were not, of course, done unassisted. I owe thanks to many colleagues some of whose names appear in the reference papers but others I was not able to reference. I would like to take this opportunity to thank them all.

Tamotsu Takahashi

# Preface to the first English edition

The Japanese edition was published in September 2004 by Kinmiraisha in Nagoya, Japan. The book was acclaimed by Japanese engineers and researchers and was awarded the Japanese Association for Civil Engineers' 'Publishing Culture Prize' for the most valuable publication of 2004. Many colleagues expressed their interest in an English edition of the book, which would make it more broadly accessible to the international academic community. One of my motivations in undertaking the translation was the previous success of the English version of my earlier book Debris Flow, published in 1991, in the IAHR monograph series. This well-known publication continues to be cited frequently in international literature. In the preface of the original work, I wrote as follows:

> The important engineering subjects of the research; identification of the hazardous ravines, prediction of occurrence time, estimation of hazardous area and the risk, functions of various structural countermeasures, design criteria of structures, warning and evacuation systems, etc., have also made considerable progress. I would like to review those problems on another occasion.

A long time has elapsed since the publication of this original book, a period in which significant progress has been achieved in Fundamental Mechanics and in the field of Engineering. The 2004 Japanese edition reflects the intention expressed above and contains improved theories. This current English edition also incorporates part of another book I have published in Japanese, entitled *Mechanisms of Sediment Runoff and Countermeasures for Sediment Hazards*, which was published in 2006.

I hope that readers all over the world will enjoy reading this book and that they will find it an interesting and helpful contribution to the literature.

January 2007
Tamotsu Takahashi

# Preface to the second English edition

The main themes in the first edition were focused on a single debris flow event and the following topics were discussed: the classification from the mechanical point of view; the characteristic behaviors of flow; the analyses and predictions of the processes during its initiation, flowing down and deposition; the reproductions of some representative debris-flow disasters using numerical simulations; and the methods for preventing or mitigating the debris-flow disasters. These themes should, of course, constitute the main parts of the second edition as well. But, from the countermeasure planning point of view, the preventing or mitigating functions of the structures should continually be shown for a long period during which many debris flows and highly sediment-laden floods occur. In this context, the analyses of sediment runoff over a long period are also important. Therefore, in the second edition, a sediment runoff model that is named 'SERMOW' and its improved version 'SERMOW ver.2' are introduced in the new chapter 6, where the sediment runoff volumes during a long period as well as the hydrograph, sediment graphs divided into several particle size groups for a single debris flow event can be predicted.

Recently, after the publication of the first edition, the large-scale landslides with the formation of landslide-dams occurred such as that induced by the Wenchuan earthquake of May 2008 in China, that induced by severe rainfall brought about by the typhoon Morakot in August 2009 at Shiaolin in Taiwan, and that induced by typhoon No. 12, in September 2011 at the Nara and Wakayama districts in Japan, among others. In this context, some considerations on the mechanics of the high mobility of large-scale deep-seated landslides and debris avalanches are added in the second edition.

Several other topics that may contribute to a deeper and more comprehensive understanding of debris flow mechanics are also added.

Fortunately, the first edition of this book was acclaimed by many readers, but a considerable time has elapsed since the publication, so that Taylor & Francis suggested me to revise. In response to the suggestion I decided to publish the second edition, renovating under the above-mentioned viewpoints.

July 2013
Tamotsu Takahashi

# About the author

**Tamotsu Takahashi** (Kyoto, 1939) graduated as a Master in Civil Engineering at Kyoto University in 1965. From 1965 to 1967, he then worked as a research assistant at the Disaster Prevention Research Institute (DPRI) of the same university and, after a year in the Civil Engineering Department as a lecturer, he returned in 1968 to the DPRI as an associate professor. With his research on flood flow dynamics in river channels, he obtained the doctoral degree in 1972. After this, he worked as a post-doctoral fellow at Lincoln College, New Zealand, where he investigated miscellaneous problems that were associated with braided rivers. Upon returning to DPRI in Japan, he put importance on the study of sediment runoff problems that were involved with debris flow and bed load on very steep slope channels. Consequently, in 1982, he was awarded a full professorship for a newly founded research section on the investigation of anti-flood hazards systems. He then added slightly more themes to his portfolio and extended his research to the water flooding and sediment problems in urban areas. From 1992 he moved to the research section on the investigation of sedimentation problems.

After his retirement in 2003, he continued working on debris flow and sediment runoff problems as a professor emeritus at Kyoto University. From 1995 to 1997 he served as the director of DPRI and during this appointment, he has reorganized the entire DPRI and has thoroughly promoted the scientific investigation of the Great Hanshin Earthquake which took place in Kobe in 1995 as the director of DPRI and the head of the Japanese Group for the Study of Natural Disaster Science. He is now working for the foundation 'Association for Disaster Prevention Research' as the chief director.

Professor Takahashi has authored numerous papers and held many invited keynote lectures. He also received several awards for his outstanding work from the Japan Society of Civil Engineers and from the Japan Society of Erosion Control Engineering. His successful book 'Debris Flow', published in 1991 by A.A. Balkema Publishers in the IAHR monograph series was the first systematic approach to the subject and is still frequently referred to. The original Japanese language version of this current new and extended edition was received very well and the author was awarded the Publishing Culture Prize from the Japan Society of Civil Engineers in 2004 for it. He was also awarded the Akagi Prize in 2008 for his outstanding contributions to the prevention and mitigation of debris flow disasters.

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Chapter 1

# What is debris flow?


The photograph shows the front part of the viscous debris flow at Jiangjia gully, Yunnan, China. It is flowing from upper right to lower left. This flow contains solids fraction more than 60% by volume. Notwithstanding such a high solids concentration, it flows fast on slopes as mild as 3 degrees.

## INTRODUCTION

Since ancient times there have been witness records of debris flows under way, stopping and depositing (e.g. Schlumberger 1882; Blackwelder 1928; their Japanese translation appears in Takahashi 1983). Thus, the nature of debris flows should have been known, at least fragmentarily, by some geographers, geologists and engineers who are concerned with works in mountain rivers. Residents in steep mountain areas in Japan have called debris flow by terms such as 'Ja-nuke', 'Yama-tsunami', and 'Yama-shio', and they have handed these terms on to the next generation to warn them of these phenomena. The meanings of these Japanese terms are 'the run off of king snake', 'the tsunami at mountain' and 'the mountain tide', respectively. But, as they have occurred in remote steep mountain and moreover in adverse conditions of severe rainstorms, there have been few scientific observational records. Therefore, no one has been able to understand why such huge boulders were easily transported down to the village on alluvial cones to cause disasters. It was a 'phantasmal disaster'.

In the last half of the 1960s scientists began to investigate the mechanisms of debris flow. Particularly in Japan, adding to the theoretical and experimental investigations, some deliberate observation systems were established in the basins where debris flow often occurs, and some clear photographic images of debris flow under way were taken for the first time in the world. Since then, some debris flow images have been shown on TV, and now the idea of debris flow phenomena is understood not only by scientists but also by the general public. When broadcasting warnings of heavy rain, the term 'debris flow' (dosekiryu in Japanese: doseki means earth and stone; and ryu means flow) is used as a widely understood phenomenon.

In this chapter, at first, various subaerial sediment moving phenomena are analyzed from a mechanical point of view, and debris flow is defined as a significant category among them. Next, referring to some observational records, debris flows are classified into three types. The characteristic differences between these three types of debris flows are explained by the physical mechanisms of the particle dispersion in the flow. Finally, the classic classifications of debris flows by the causes of occurrence and the relationship between occurrence and rainfall characteristics are explained.