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論文題目	Physical and Numerical Modelling of Co-seismic Coastal Landslides-Generated Tsunamis （沿岸域の地震時地すべりによる津波の模型実験と数値解析）		

Earthquakes primarily generate tsunamis, but landslides can often generate tsunamis. According to recent findings, tsunamis were created by underwater landslides caused by massive earthquakes. Experiments on tsunamis generated by submarine landslides and partly-submerged landslides have been less studied because of the challenge of reproducing the slope as it starts moving under the water. The time evolution of a landslide is the most important for calculating the tsunami amplitudes. To date, laboratory experiments simulating the tsunamis induced by earthquake-triggered landslides have not been developed.

This research attempted to address the research gaps in understanding the mechanism and hazard assessment of tsunamis generated by earthquake-triggered landslides by conducting physical and numerical modelling. The objectives of this study are (i) to reproduce the process of an earthquake-induced landslide causing a tsunami; (ii) to investigate the effects of landslide kinematics on wave generation under different conditions; (iii) to validate the landslide-generated tsunami model based on the centrifuge test results. (iv) to propose and validate a new dual-source model (earthquake + landslide) for the 2018 tsunami disaster in Palu Bay. There are six chapters in this dissertation. The following is a summary of the main contents of each chapter.

The first chapter provides an overview definition, classification, and history of landslide-generated tsunami events.

Chapter 2 comprehensively reviews the physical and numerical modelling of landslide-generated tsunamis. Then, the current research gaps in landslide tsunamis are discussed. There are a few numerical models but no physical modelling, including earthquake-triggered landslide-generated tsunamis. This study intends to bridge this gap by experimentally investigating landslide initiation, and validating the coupling of well-known landslide and tsunami models.

Chapter 3 discusses centrifuge modelling, principles, and scaling laws for landslide and tsunami waves. This chapter also presents the experimental procedures and the repeatability of centrifuge experiments. Then, the landslide kinematics, including the slope deformation and excess pore-water pressure, are discussed. In addition, this chapter presents the characteristics of landslide-generated tsunamis. The slope failed with time; although the decline of slope surface is rapid, the landslide volume is a time-dependent variable. The initial movement of landslide mass is essential for predicting the amplitudes of an initial tsunami wave. The initial acceleration and landslide volume were found to have a linear relationship with the first trough wave amplitude. The submarine landslide produces a first negative wave, and the second wave amplitude is much smaller than the first wave. This means the tsunami waves decay fast.

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Chapter 4 introduces a coupling of the landslide-generated tsunami model and compares the simulation results with centrifuge experimental results. The parametric studies of the model are also discussed. The landslide-induced tsunami models (LS-RAPID + LS-Tsunami) were validated using the parameters obtained from centrifuge experiments. Also, a series of ring shear tests were conducted to gather the input parameters for a simulation model. The model results reproduced laboratory results well with less than 10 % numerical errors. The motion of the landslide and the generation of tsunami waves were both replicated with reasonable precision. It should be noted that the landslides in this study are very rapid, so that they could be valid for the model assumption. However, there are slight differences in the phase of waves. Similar to the centrifuge results, the parametric studies show that the dimensionless landslide volume has a linear relationship with the dimensionless trough wave. In addition, the dimensionless trough wave has a second-order polynomial form with relative submerged depth.

Chapter 5 introduces the study site in Palu, Indonesia. The author proposes a new dual-source model to simulate the coastal landslide tsunami on 28 September 2018 in Palu Bay. The model's accuracy was validated based on the tide gauge data at the Pantoloan and observed data of the tsunami height and run-up. This chapter also discusses the results from the sensitivity of the dual model. From the observed data, the 2018 Palu event indicated that significant strike-slip earthquakes might cause destructive and devastating tsunamis, to which multiple source mechanisms can contribute. This is called the cascading effect of an earthquake, where a primary hazard (earthquake) causes a secondary hazard (earthquake-induced landslides), and both hazards (earthquake + landslides) are sources of tsunamis. Similar to the previous studies, our simulations confirmed that the earthquake-generated tsunami run-up height is significantly smaller than the observed data. This strong evidence indicates that a secondary source (landslides) was highly likely involved. This study reproduces all landslides inside Palu Bay, whose sites are confirmed through previous marine bathymetric and other investigations. The landslide model can explain the high tsunami height in southern Bay. It can be concluded that the landslide source rather than the earthquake is the major cause of the local high tsunami inside Palu Bay. A numerical simulation of the dual model provided a better match with the tsunami observation records than a simulation based on earthquakes or landslides alone. The dual model can recreate all observed data, especially the high tsunami wave in the South of the Bay. Parametric studies on changing the soil properties of LS-E, SLS-H, and SLS-I were examined to see the role of a landslide-generated tsunami. Based on the results from these simulations, the most exciting result is that the LS-E, SLS-H, and SLS-I played an essential role in the highest tsunami height in the north of the Bay.

Chapter 6 gives the research summaries and conclusions. In addition, some suggestions for further research are provided.

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　本論文は、地震によって発生する沿岸部の海底地すべりによって引き起こされる津波を模型実験や数値解析を用いて評価することを目的としたものである。海底地すべりによる津波の発生過程はこれまでも検討されているが、簡易な地すべりブロックの運動に着目しているものなど、地震時の海底斜面の地すべり挙動から津波の発生過程までを包括的に検討した研究は少ない。そこで、本研究では遠心模型実験や数値解析を用いて、水浸した砂質土斜面の地震時の地すべり挙動が津波の波形に与える影響を調べた。

　遠心模型実験では、完全あるいは部分的に水浸した砂質土斜面を対象として、加振による斜面の変形と発生する水面変動の関係を検討した。実験では斜面を構成する土の密度や入力する加振の大きさが発生する水面変動に与える影響を検討した。計測された水面波形から土槽壁の影響を取り除くためローパスフィルターを適用した。実験の結果、加振時の斜面の変形による水面変動波形において、第１波の谷波形の振幅は継続の山波形の振幅の二倍程度になること、その振幅は地すべり体積やその運動の初期加速度に依存していることを示した。

　数値解析では､斜面安定と破壊後の地すべり運動を評価可能な既存の解析コードと、海底面の変化による水面の変位とその伝播を評価可能な既存の非線形潜水方程式をもとにした解析コードを組み合わせた解析手法を用いた。遠心模型実験で用いた砂質土についてはリングせん断試験などを実施して力学特性を把握した。数値解析は遠心模型実験で得られた加振時の砂質土斜面の変形や水面変動をよく再現しており、解析手法の妥当性を確認した。また、パラメータスタディにより地すべり体積や斜面の水浸深度が水面変動に与える影響を明らかにした。

　最後に、地震断層と海底地すべりの両方を津波発生源として考慮した津波解析手法を開発し、2018 年インドネシア・パル湾での津波観測との比較を通じて解析手法の妥当性を確認した。先行研究により得られた地震断層や海底地すべりの情報を用いて行った複合解析の結果、津波観測の結果をよく再現し、地震断層よりも海底地すべりが津波高さに与える影響が大きいことを示した。

　以上のように､本論文は沿岸域の地震時地すべりによる津波の波形について実験的・解析的に評価したものであり、今後の津波防災に対して有益な知見を与えるものと評価できることから、学術上、実際上寄与するところが少なくない。よって、本論文は博士（工学）の学位論文として価値あるものと認める。また、令和５年４月２１日、論文内容とそれに関連した事項について試問を行って、申請者が博士後期課程学位取得基準を満たしていることを確認し、合格と認めた。

　なお、本論文は、京都大学学位規程第１４条第２項に該当するものと判断し、公表に際しては､（令和６年３月３１日までの間）当該論文の全文に代えてその内容を要約したものとすることを認める。