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Seismic behaviour of creeping landslides at the flanks of water reservoirs

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Summary

Landslides are a global threat in mountainous regions, causing thousands of fatalities every year. Less attention is paid to active, slow-moving or also called creeping landslides because they do not usually manifest themselves in catastrophic events, but can cause severe damage to buildings and infrastructures. They are characterised by a mobile state that is highly sensitive to environmental influences. As a result, they are often thought to be particularly susceptible to seismic acceleration, which is even supported by conventional simplified models. Unfortunately, corresponding field observations are very rare, but they tend to show only small co-seismic landslide displacements. The potential consequences of a landslide collapse, for instance on the flank of a water reservoir, underlines the importance of reliable mechanical models and a better understanding of the behaviour.

Due to its hilly and mountainous topography, Switzerland is particularly affected by the impacts and hazards of landslides. On the one hand, due to the dense population, various structures and infrastructures are in direct contact with landslides and can already suffer massive damage due to the annual creep movements. The situation is much more critical in context of lakes and dams. A high acceleration of a landslide, the so-called collapse, can cause impulse waves, which, depending on the location and volume, can have devastating consequences. Countless catastrophic landslide events triggered worldwide every year by earthquakes illustrate that seismic triggering of creep slopes is indeed possible and therefore needs to be better investigated. However, due to the complex hydro-mechanical conditions, such analyses and assessments are still limited. Therefore, highly simplified methods are usually used, which do not allow a reliable risk assessment.

The Swiss Federal Office of Energy (SFOE) has therefore initiated a research project at the Geotechnical Institute of the ETH Zurich (IGT). The main objective is to gain a profound understanding of the behaviour of slow-moving landslides in the event of an earthquake. For this purpose, new models are to be developed that can simulate potential velocities and displacements and allow a risk assessment of a catastrophic collapse. As a part of this project, a specific landslide at a reservoir in Switzerland has been selected as a case study and is instrumented with state-of-the-art measurement technology. This allowed for a detailed geotechnical model of the landslide to be created and for the novel methods developed to simulate the earthquake impact to be applied.

This report includes the basic mechanics of slow-moving active landslides, the results of the research project and, finally,recommendations for the assessment of landslides subjected to seismic loading.

Zusammenfassung

Rutschungen sind eine weltweite Bedrohung in Gebirgsregionen und fordern jedes Jahr tausende Todesopfer. Weniger Beachtung erfahren aktive, sich langsam bewegenden Rutschungen, sogenannte Kriechhänge, da diese in der Regel keine katastrophalen Ergebnisse verursachen. Diese können jedoch grosse Schäden an Gebäuden und Infrastruktur verursachen. Kriechhänge sind charakterisiert durch einen mobilen Zustand, welcher anfällig auf Umwelteinflüsse ist, weswegen davon ausgegangen wird, dass diese besonders leicht durch Erdbeben beschleunigt werden können. Diese Vermutung wird durch konventionelle, vereinfachte Modelle gestützt. Leider sind entsprechende Feldmessungen äusserst selten, zeigen aber bei den wenigen bekannten Fällen meist nur kleine koseismische Verschiebungen der Rutschung. Die potenziellen Konsequenzen im Falle eines Kollapses, zum Beispiel bei einer Rutschung am Ufer eines Stausees, betonen die Bedeutung zuverlässiger mechanischer Modelle und eines besseren Verständnisses deren Verhaltens.

Die Schweiz ist aufgrund der hügeligen und gebirgigen Topografie besonders von den Auswirkungen und Gefahren von Rutschungen betroffen. Zum einen sind aufgrund der dichten Besiedelung diverse Bauwerke und Infrastrukturen in direktem Kontakt mit Rutschungen und können bereits aufgrund der jährlichen Kriechbewegungen massive Schäden erleiden. Deutlich kritischer ist die Situation in Zusammenhang mit Seen und Stauanlagen. Eine starke Beschleunigung einer Rutschung, der sogenannte Kollaps, kann Flutwellen verursachen, welche je nach Standort und Volumen verheerende Konsequenzen mit sich ziehen können. Unzählige katastrophale Rutschereignisse, welche weltweit jedes Jahr durch Erdbeben ausgelöst werden, verdeutlichen, dass eine seismische Triggerung von Kriechhängen durchaus möglich ist und daher besser untersucht werden muss. Aufgrund der komplexen hydro-mechanischen Bedingungen ist jedoch eine solche Analyse und Beurteilung nur beschränkt möglich. In der Regel kommen daher stark vereinfachte Methoden zum Einsatz, welche keine zuverlässige Risikobeurteilung erlauben.

Das Bundesamt für Energie (BFE) hat daher ein Forschungsprojekt beim geotechnischen Institut der ETH Zürich (IGT) in Auftrag gegeben. Das Hauptziel ist ein fundiertes Verständnis des Verhaltens von Kriechhänge im Erdbebenfall. Dazu sollen neue Modelle entwickelt werden, welche eine Risikobeurteilung eines katastrophalen Kollapses erlauben und allfällige Geschwindigkeiten und Verschiebungen simulieren können. Als Teil dieses Projekt wurde auch eine bestimme Rutschung bei einem Stausee als Fallstudie ausgewählt und mit modernster Messtechnik instrumentiert. Dies erlaubte es, ein detailliertes geotechnisches Modell der Rutschung zu erstellen und die entwickelten Methoden zur Simulation des Erdbebenfalls anzuwenden.

Dieser Bericht befasst sich mit den Grundlagen der Mechanik von Kriechhängen, den Resultaten des Forschungsprojektes und schlussendlich den Empfehlungen zur Beurteilung von Rutschungen im Erdbebenfall.

Résumé

Les glissements de terrain constituent une menace mondiale dans les régions montagneuses, causant des milliers de morts chaque année. On accorde moins d'attention aux glissements de terrain actifs sujets à des mouvements lents ou dits de reptation, aussi appelés « creeping landslides », car ils ne se manifestent généralement pas par des événements catastrophiques, mais peuvent causer de graves dommages aux bâtiments et aux infrastructures. Ils se caractérisent par un état mobile très sensible aux influences environnementales. Par conséquent, on pense souvent qu'ils sont particulièrement sensibles à l'accélération sismique, ce que confirment aussi les modèles simplifiés conventionnels. Malheureusement, les observations de terrain correspondantes sont très rares, mais elles ont tendance à ne montrer que de faibles déplacements de glissements de terrain co-sismiques. Les conséquences potentielles de l'effondrement d'un glissement de terrain, par exemple sur le flanc d'un réservoir de barrage, soulignent l'importance de modèles mécaniques fiables et d'une meilleure compréhension du comportement.

En raison de sa topographie vallonnée et montagneuse, la Suisse est particulièrement touchée par les impacts et les dangers des glissements de terrain. D'une part, en raison de la densité de la population, diverses structures et infrastructures sont en contact direct avec les glissements de terrain et peuvent déjà subir des dommages importants en raison des mouvements de reptation annuels. La situation est beaucoup plus critique en ce qui concerne les lacs et les barrages. Une forte accélération d'un glissement de terrain, appelée effondrement, peut provoquer des vagues qui, selon l'endroit et le volume, peuvent avoir des conséquences dévastatrices. D'innombrables glissements de terrain catastrophiques déclenchés par des tremblements de terre dans le monde entier chaque année illustrent le fait que le déclenchement sismique de pentes en reptation est effectivement possible et qu'il doit donc être mieux étudié. Cependant, en raison de la complexité des conditions hydromécaniques, les méthodes d’analyse et d’évaluation sont encore limitées. Par conséquent, des méthodes très simplifiées sont généralement utilisées, ce qui ne permet pas une évaluation fiable des risques.

L'Office fédéral de l'énergie (OFEN) a donc lancé un projet de recherche à l'Institut de géotechnique de l’ETH Zürich (IGT). L'objectif principal est d'acquérir une compréhension approfondie du comportement des glissements de terrain lents en cas de tremblement de terre. Pour ce faire, de nouveaux modèles doivent être développés afin de simuler les vitesses et les déplacements potentiels et de permettre une évaluation du risque d'effondrement catastrophique. Dans le cadre de ce projet, un glissement de terrain spécifique à un réservoir en Suisse a été sélectionné comme étude de cas et a été instrumenté avec une technologie de mesure de pointe. Cela a permis de créer un modèle géotechnique détaillé du glissement de terrain, d'appliquer et de valider les méthodes développées pour simuler le cas d'un tremblement de terre.

Ce rapport comprend la mécanique de base des glissements de terrain actifs à déplacement lent, les résultats du projet de recherche et enfin des recommandations pour l'évaluation des glissements de terrain lors d'un séisme.

Contents

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1 Introduction

1.1 Background information and current situation

Creeping landslides are a natural hazard typical for many mountainous areas. The growing demand for space in mountainous areas due to expansion of infrastructure and housing leads to increased interaction between manmade structures and existing slope instabilities. Examples of problems that arise from construction on creeping landslides are numerous. They include cases of villages that are fully or partially built on creeping slopes like Braunwald (Schindler, 1982) or St. Moritz (Schlüchter, 1988), where the movement of the landslide causes continuous damage to the houses and structures built in these slopes. In other cases important traffic infrastructure is threatened by a creeping slope, such as the Ganter Bridge at the Simplon Pass (Puzrin and Schmid, 2012, Puzrin et al., 2012), requiring expensive mitigation measures to be implemented. A special class of problems caused by creeping landslides concerns artificial reservoirs e.g. for the generation of hydropower energy. Continuous existing movement of the reservoir flanks or reactivation of a dormant creeping landslide due to filling of the reservoir endanger both the reservoir operation and the downstream communities. To reduce the threat posed by the instable flanks extensive stabilization works and monitoring programs are necessary (e.g., the Clyde power project in New Zealand, Macfarlane, 2009). In order to design stabilization works and early warning systems, a clear understanding of the landslide mechanics under normal and extreme conditions (heavy rain and earthquakes) is necessary.

Two major threats related to the creeping landslides can be distinguished: (i) First, continuous movements of the landslide can cause damages to structures built on top or inside the landslide. (ii) Second, creeping landslides can accelerate to the point that the landslide becomes unstable, as was the case with the Vaiont landslide, where a pre-existing creeping landslide collapsed into a reservoir causing an impulse wave which went over the dam and destroyed the village downstream (Alonso et al., 2010).

This catastrophe clearly shows why a thorough understanding of the mechanisms governing the behaviour of such landslides is of great importance in order to perform a reliable assessment of the threat posed by creeping landslides at the flanks of reservoirs, especially in the case of earthquakes.

Despite a significant progress in modelling of creeping landslides behaviour under transient loading (precipitation) in general (Glastonbury and Fell, 2008, Laloui et al., 2009, François et al., 2007), and also at the IGT (e.g. Puzrin and Schmid, 2011, Puzrin and Schmid, 2012, Puzrin et al., 2012, Oberender and Puzrin, 2016), the effects of earthquake loading largely remain an open question. This is a significant problem particularly for high risk structures such as reservoirs, because due to their high damage potential in case of failure, they have to be designed for extreme events of large return period including very strong earthquakes.

The lack of reliable models for earthquake performance of creeping landslides is not only due to the absence of consistent observations of landslide behaviour during earthquakes but also due to the complexity of phenomena and interactions that govern the behaviour of creeping landslides during seismic loading. These phenomena include: (i) the rate dependency of shear strength along the boundary between stable and instable soil, (ii) the strain dependent reduction of shear strength along the same boundary, (iii) build-up of excess pore pressures during earthquake loading, (iv) complex boundary conditions in the landslide's toe region. Combination of the above factors can lead to a failure of the landslide body followed by a mechanically and geometrically non-linear post-failure landslide evolution.

Most of the existing approaches for seismic slope stability analysis, such as pseudo static approaches, dynamic finite element models or Newmark's method (Newmark, 1965, Abramson, 2002), if at all applicable, neglect at least several of these phenomena. This may lead to a non-conservative overestimation of the landslides safety during seismic loading.

1.2 Objectives

The ultimate goal of this research is to achieve a better understanding of the behaviour of active slow-moving landslides during earthquakes, including potential instability and subsequent sliding velocities. In the process, a computational framework for analysis of seismic response of creeping landslides will be developed. The framework will be based on suitable formulations of the corresponding boundary value problems, including necessary constitutive models and the guidance on how to determine the parameters of these models. A numerical tool will be developed to solve the boundary value problems and used for the analysis of the seismic response of a number of typical creeping landslides.

For the particular case of landslides around reservoir lakes, the questions if a collapse during an earthquake is possible and what landslide velocities can be reached will be investigated, in order to provide parameters for calculating the height of a potential impulse wave. But even if a failure could be ruled out, deformations of the landslide might still damage installations of the reservoir (e.g. blockage of the bottom outlet) or the dam itself; consequently also the question of how much deformation is to be expected in the non-failure case will be subject of investigation in this research. Towards the goal the following objectives will be achieved.

Objective 1: Survey of a number of creeping landslides in Switzerland, with a systematic recording of existing soil conditions, geometries, boundary conditions, reaction to pore pressure changes, etc.. This survey is intended to result in a structured catalogue of landslide features at different sites that can form the basis for this investigation and, potentially, for future landslide research.

Objective 2: Mechanical and mathematical formulation of the boundary value problem for the creeping landslides including different possible geometries, boundary conditions, possible seismic loadings and determination of phenomena necessary to capture in order to model seismic behaviour of landslides. The complexity of the formulation will depend on the conditions found at the specific sites. It is planned to keep the formulation as simple as possible in order to ensure applicability of the method, but yet to be able to reproduce all the important phenomena.

Objective 3: Establishing constitutive models capable of reproducing the phenomena that are governing the behaviour of the landslide during seismic loading; in particular (i) rate dependency of shear strength on the slip surface and (ii) development of excess pore pressures in the material surrounding the slip surface. To find suitable constitutive models laboratory tests will be conducted and combined with field observations. When possible, established models from literature will be adopted, otherwise new models will be developed.

Objective 4: Development of the computational tool for numerical solution of the formulated boundary value problems incorporating the constitutive models from the previous objectives. The formulation of the boundary value problem and the constitutive models will be integrated and solved numerically. The method used to achieve this will depend on the complexity of the problem and the constitutive models.
Objective 5: Parametrical studies aiming to establish expected ranges of landslide displacements and velocities for typical landslide geometries, soil and boundary conditions and seismic loading. This will allow investigating the sensitivity of parameters and giving feedback on what aspects might need additional investigation. The developed framework will also be applied to selected real landslide case studies.

Objective 6: Recommendations for engineering practice. The methods and tools developed during the investigation will be documented in order to ensure a transfer of knowledge to practitioners. Further dissemination of the project results will be achieved via scientific publications and technical presentations for scientific and engineering audiences.

1.3 About this report

This report summarizes the findings and recommendations of the BFE research Project **Seismic behaviour of creeping landslides at the flanks of water reservoirs**. More details with respect to the findings may be found in the following resulting publications:

- Kohler, M. (2023). Effects of Earthquakes on the Mechanics of Active Landslides. ETH Zurich. PhD Thesis.
- Kohler, M., Hodel, D., Keller, L., Molinari, A. & Puzrin, A. M. (2023). Case study of an active landslide at the flank of a water reservoir and its response during earthquakes. Engineering Geology. https://doi.org/10.1016/j.enggeo.2023.107243
- Kohler, M., Hottiger, S. & Puzrin, A. M. (2023). Rate, water pressure and temperature effects in landslide shear zones. Journal of Geophysical Research: Earth Surface.

- Kohler, M. & Puzrin, A. M. (2022). Mechanism of co-seismic deformation of the slow-moving La Sorbella landslide in Italy revealed by MPM analysis. Journal of Geophysical Research: Earth Surface, 127(7), e2022JF006618. https://doi.org/10.1029/2022JF006618
- Kohler, M. & Puzrin, A. M. (2023). Mechanics of coseismic and postseismic acceleration of active landslides. Communications Earth & Environment, in press.
- Kohler, M., Stoecklin, A. & Puzrin, A. M. (2021). A MPM framework for large deformation seismic response analysis. Canadian Geotechnical Journal. https://doi.org/10.1139/cgj-2021-0252
- Kohler, M., Stoecklin, A. & Puzrin, A. M. (2022). Material point method for large deformation seismic response analysis. ECCOMAS Congress 2022 - 8th European Congress on Computational Methods in Applied Sciences and Engineering, Science Computing. https://doi.org/10.23967/ECCOMAS.2022.171

In case a particular landslide is being investigated it is highly recommended to also study these more comprehensive reports or potentially contact the authors for advice.

2 Fundamental mechanics of co- and post-seismic displacement of a creeping landslide

2.1 Governing Phenomena

This Chapter is based on chapters 1 and 7 from Kohler (2023).

A number of existing models that attempt estimating displacements of active landslides during earthquake:

i. Rigid sliding block analysis as introduced by Newmark (1965) in his Rankine lecture and is better known as Newmark's sliding block analysis.

ii. More sophisticated approaches with compliant sliding blocks, e.g. Kramer & Smith, 1997; Lin & Whitman, 1986; Makdisi & Seed, 1978; Rathje & Bray, 1999.

iii. Fully coupled analysis (Rathje & Bray, 1999) when the dynamic properties of the sliding mass and the subsoil as well as the permanent displacements are modelled permanently.

It has to be noted that the sliding block approaches, both with rigid or compliant blocks are intended mostly for initially stable slopes. In all these models the plane on which the landslide moves (slip surface) is being modelled as a distinct surface. Cases where the velocity field of the sliding slope is diffuse may need different approaches, but can still draw some knowledge from slip surface models.

In case the creeping slopes being modelled comprehensively the following phenomena are likely to be heavily influence the reaction of the slope during seismic loading:

i. Rate dependence of the shear resistance along the slip surface.

ii. Structural softening (or hardening) along the slip surface.

iii. Pore pressure fluctuations along the slip surface due to changes in reservoir level or precipitation.

iv. Geometry of the slope and change of the geometry in case of large deformations (e.g. geometric hardening).

v. Development of excess pore pressure around the shear zone that can propagate into the shear zone and therefore further reduce the shear resistance (pore pressure induced softening). However, this effect is more important when looking at the post-seismic behavior of such slopes.

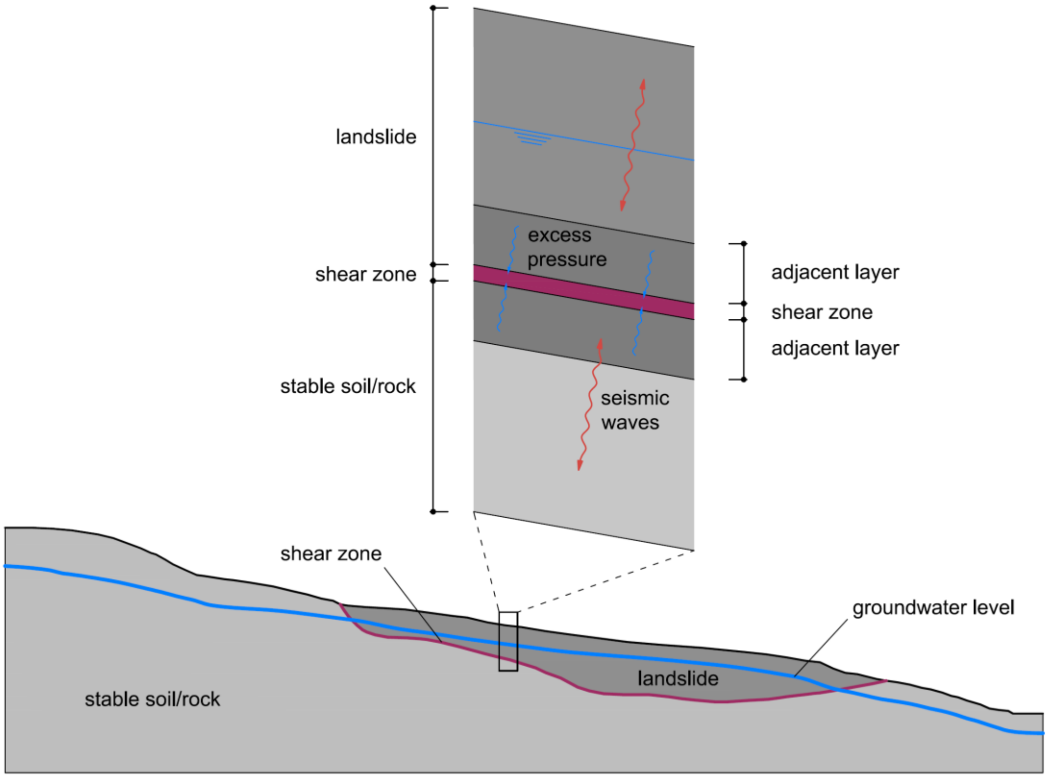

Figure 2.1: Schematic representation of a creeping landslide

Figure 2.1 shows a schematic representation of the landslide and its section. In very general terms, a landslide consists of a stable ground (soil or rock), the landslide itself (or sliding mass) and the shear zone where the movement is localised. In most cases, a groundwater table is also of crucial importance. In the event of an earthquake, layers adjacent to the shear zone may also be important, as potential pore water pressure could there be generated and then propagate into the shear zone. However, many landslides are much more complex and cannot always be simplified in this way.

In the following sections the different phenomena are described and illustrated phenomenologically additional simplified equilibrium equations are given to describe the phenomena mathematically. Note, however, that these equations are based in strong simplifications of the problem and are only aiming to give some fundamental insight into the problem formulation.

Rate decency (i) of the shear resistance along the shear zone is the most important phenomenon that ensures the balance of an active landslide. At the same time this phenomenon is extremely difficult to measure. For a simple slope of constant thickness and inclination of purely frictional material the equilibrium of driving forces due to weight of the landslide and resisting forces may be written as:

$$\gamma h \sin(\alpha) = \big((\gamma h)\cos(\alpha) - u\big) \cdot (\mu + \Delta\mu(\dot{\varepsilon_s})) \tag{2.1}$$

where γ is the soil weight, h the landslide height, α the inclination of the shear zone, u the static pore water pressure, μ the static friction coefficient, $\Delta\mu$ the rate dependent friction coefficient that depends of the $\dot{\varepsilon_s}$ rate in the shear zone. The landslide is active since the static resistance is not sufficient to keep the slope in equilibrium:

$$\big((\gamma h)\cos(\alpha) - u\big) \cdot\ \mu < \gamma h \sin(\ \alpha) \tag{2.2}$$

In case of strain softening (ii), the shear resistance decreases with increasing accumulated shear strain and therefore with increasing displacements of the landslide. In case of clayey soils the rearrangement of clay particles is responsible for the structural softening. For "old" landslides it may be assumed that the shear zone has formed completely, i.e. no further loss of resistance due to structural softening may be expected. However, in case when the landside has not yet fully formed (i.e. the instable area grows), or in case where the landslide is constraint by an stabilizing intact part of material, it is very important to assess whether the stabilizing part can fail during earthquake, which can trigger a potentially catastrophic collapse of the landslide. In such cases the strain softening equation (2.2) may be amended as:

$$\gamma h \sin(\ \alpha) = \big((\gamma h) - u\big)\cos(\alpha) \cdot \big(\mu_0 - \Delta\mu(\varepsilon) + \Delta\mu(\dot{\varepsilon_s})\big) \tag{2.3}$$

The loss of shear resistance due to softening $\Delta\mu(\varepsilon)$ thus has to be compensated by an increase of shear resistance du to rate effects $\Delta\mu(\dot{\varepsilon_s})$. This means the landslide has to move faster the more shear resistance is lost due to softening. In case the loss of strength due to softening cannot be compensated due to rate effects the landslide will accelerate dramatically.

Pore pressures (iii) acting in the slip surface are influenced by precipitation and snowmelt and in case of landslides along reservoir flanks also by the water level in the reservoir. For the transient state (i.e. pore pressure fluctuations induced due to external influence) equation (2.3) can be rewritten as

$$\gamma h \sin(\ \alpha) = \big((\gamma h) - u - \Delta u_{trans}\big)\cos(\alpha) \cdot \big(\mu_0 - \Delta\mu(\varepsilon) + \Delta\mu(\dot{\varepsilon_s})\big) \tag{2.4}$$

where Δu_{trans} represents a transient pore water pressure change. This means that in case of an increasing pore pressure e.g. due to water infiltration during snowmelt, shear resistance will drop which again has to be compensated by an increase in rate dependency, i.e. the landslide will accelerate and move at a higher speed the higher the pore pressure acting along the slip surface.

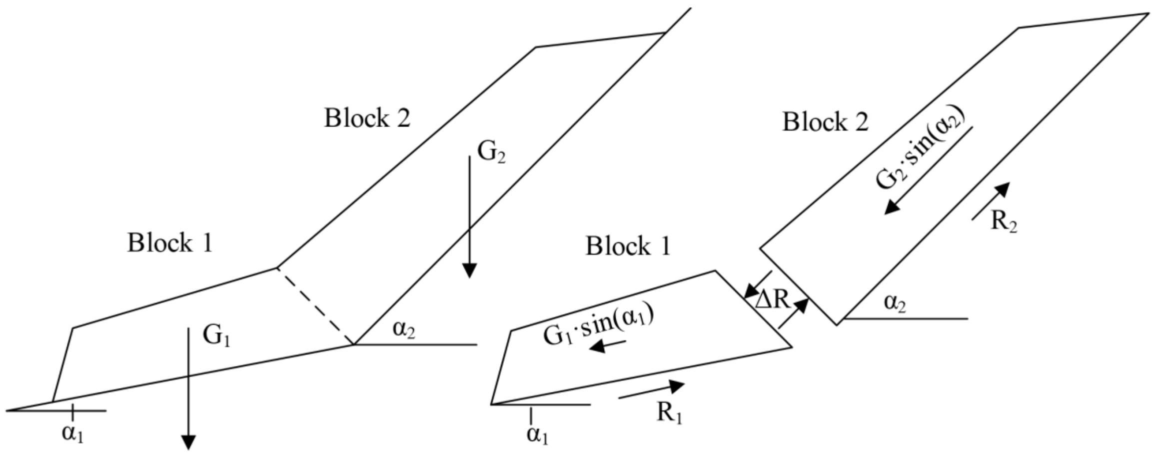

Figure 2.2: Simplified representation of landslide with varying inclination as two blocks.

The geometry of the landslide (iv) influences heavily its kinematics. Essentially the geometry of the shear zone influences how much of the landslides mass acts stabilizing or destabilizing respectively. Simplifying the geometry of a landslide into one stabilizing and one destabilizing part the landslide can be represented as shown in Figure 2.2.

Consequently, the additional mass acting in the stabilizing part (block 1) will cause it to move at a higher strain rate (and thus velocity) whilst the more instable part will move at a lower strain rate (velocity) as it would without the stabilizing part. In an extreme case, the stabilizing part prevents the more instable part from accelerating catastrophically. As the landslide moves during an earthquake, mass is being transferred into the stabilizing part. However, if the stabilizing part fails or the geometry is less favourable (e.g. downwards increasingly inclined slope) the landslide may also accelerate.

Note, the effect of large landslide deformations and the subsequent change of the landslide geometry are difficult to model and simplified relations often fail to account for the complexity of this phenomenon sufficiently. Also, classical numerical approaches like standard FEM cannot readily deal with large deformations. Therefore, special numerical techniques are necessary, like Eulerian-Lagrangian FE formulation. In this work, the so-called material point method (MPM) has been applied to model large deformations in landslides. Since this relatively new method has not been used in the context of seismic loading it has been extended to be used for studies of earthquake loading.

Lastly, depending on the material properties of the landslide body there is the possibility of excess pore pressure (v) generation during seismic loading. In the shear zone itself, the generation of excess pore pressures is still under debate. Assuming that the shear zone is fully softened, one would not expect further volumetric contractive behaviour and thus no potential for excess pore pressure development. However, this may only be true for shear zones dominated by clayey material, in other cases like sand or rock, crushing of grains or development of heat during fast shearing may cause significant excess pore pressures inside the shear zone. These phenomena are not discussed further herein but should be assessed for specific cases.

With respect to the not yet sheared material of the landslide body and the underlying stable soil adjacent to the shear zone, excess pore pressure development can be expected during strong seismic loading. This excess pore pressure can propagate into the shear zone during and more importantly after an earthquake, which might cause larger landslide velocities and accumulated displacements during and after the earthquake. The permeability of the landslide body controls how fast the excess pore pressure can dissipate. Equation (2.4) may be rewritten as

$$\gamma h \sin(\alpha) = \left((\gamma h) - u - \Delta u_{trans} - \Delta u_{excess}\right) \cos(\alpha) \cdot \left(\mu_0 - \Delta\mu(\varepsilon) + \Delta\mu(\dot{\varepsilon}_s)\right) \quad \textbf{(2.5)}$$

As can be seen, if the absolute value of the excess pore water pressure Δu_{excess} grows, also the rate dependent friction $\Delta\mu(\dot{\varepsilon}_s)$ and thus the shear strain rate needs to grow.

Note that the functional representation of the growth of shear resistance with rate is widely unknown. Therefore, it is possible that at large strain rates no additional shear strength can be mobilized, which in turn means that a sufficiently large drop of effective stresses due to excess pore pressures may cause a dramatic acceleration of the landslide. Some authors even report a drop in shear strength at very fast loading (strain rate softening). Consequently, the material of the shear zone should either be tested or at least classified and compared with tests from literature to get a feeling what kind of behaviour is to be expected.

2.2 The potential of catastrophic landslide collapse

Catastrophic failure of a landslide means represents the situation where no further resisting forces can be mobilized and the unbalance of driving and resisting forces causes the landslide to accelerate dramatically. Whether a catastrophic collapse of a creeping landslide is possible or not, is extremely difficult to assess. Fundamentally, a creeping landslide is already in a state of failure. Catastrophic collapse of the slope is avoided either by rate dependency of the shear strength or geometrical effects.

In case rate effects are neglected in the assessment of the catastrophic failure, the geometry of the landslide is essential. The maximum velocity of the landslide and how far it moves need to be critically assessed. Consequently, such assessment relies heavily on an appropriate knowledge of the geometry of the landslide.

If the landslides geometry does not have a significant stabilizing effect on the landslide in case of collapse, the other stabilizing effect may be rate dependency of the shear strength in shear zone. However, quantifying this effect is very difficult. In order to assess it two options are possible.

- Use of field measurements to assess the effect of rate dependency. This requires monitoring of landslide velocity and pore pressures on shear zone over a longer period with varying environmental conditions. Using these measurements or more specifically the relation between pore pressure fluctuations and velocity it may be possible to estimate a rate dependency formulation that describes the transient behaviour of the landslide.

- Use of laboratory measurements to assess the effect of rate dependency. In order to assess rate dependency in a laboratory set up, ring shear tests are today the only possible method that allows to have a sample undergoing unlimited shear deformations. This allows varying the shearing velocity in order to measure the relation between shear strength and shear velocity. However, the immense challenge for these tests is, that the effect that is intended to be measured is very small. Therefore, all potential sources of disturbance need to be minimized in order to get reliable measurements of the effect under investigation. In this work, a ring shear device capable of this is presented as well as tests on different materials. However, still it is very difficult to perform tests ranging from a very low strain rate of a creeping landslide to the potentially immense rates during an earthquake.

In general, the assessment of catastrophic failure remains extremely challenging. In a first step, the possible consequences should therefore be determined under conservative soil properties and geometry. In a second step, the geometry can then be taken into account more precisely so that the velocity and displacement can be better estimated. Only in a final step is it recommended to better represent the material properties, as this is associated with great effort and uncertainty.

Since active landslides are in a state of failure it is particularly important to identify landslides for which this state is not fully developed. These landslides still have the potential to develop failure mechanisms for which the rate dependent shear strength is not sufficient to prevent a catastrophic acceleration. Therefore, it is crucial that engineers and geologists identify situations where such acceleration is possible. For example, among other potential situations, there are:

- Landslides that are constraint by a stabilizing soil or rock outcrop that can fail during seismic loading.
- Landslides that consist of thick layers of loose soil that can be compacted during seismic loading leading to the generation of excess pore water pressure.
- Landslides where the shear zone has not yet fully propagated, i.e. further parts of a slope can be mobilized due to shear zone propagation.
- Landslides that are moving towards a steeper part of the slope, i.e. during an earthquake the material of a landslide could be pushed into a region where it collapses catastrophically.

These are only examples of potential situations, which can cause a catastrophic collapse during loading. Therefore, the assessing engineer needs to study at least qualitatively potential failure mechanisms of a landslide under investigation.

2.3 Case studies to investigate and demonstrate the modelling approach

In two case studies, the mechanics of active landslides are extensively investigated and suitable modelling approaches are shown.

La Sorbella landslide (Italy)

Using the case of the La Sorbella landslide in Italy, chapter 3 of Kohler (2023) and Kohler, M. & Puzrin, A.M. (2022) demonstrate the use of monitoring data to calibrate a numeric model of the landslide using Material point method (MPM). This model is capable to deal simultaneously with extremely slow deformations and with large deformations during seismic loading. The results of this study show that for the La Sorbella landslide the seismic behaviour is heavily dependent on the interaction of some of the phenomena: rate effects, softening along the shear zone and the surrounding material and geometrical effects.

Marsc landslide (Switzerland)

Within the scope of this research project the Marsc landslide at the flank of the Luzzone reservoir has been extensively monitored and its mechanics have been studied. This can be found in Chapter 6 of Kohler (2023) and in Kohler et al. (2023). The combination of field monitoring to calibrate the landslide kinematics under transient (non-seismic) loading and laboratory tests to assess the rate effects along the slip surface in case of fast (seismic) loading are shown. This allows calibrating a MPM model of the landslide to simulate its response during earthquakes in different scenarios.

3 Co-seismic behaviour of active landslides

In this chapter, the co-seismic behaviour of landslides is discussed. First, the modelling of active landslides during earthquakes using the Material Point Method is introduced. This is followed by the specific application to slow-moving landslides, with a focus on the calibration of the corresponding models using field and lab data. The contents of this chapter are based on the published articles (Kohler, Hodel et al., 2023; Kohler, Hottiger et al., 2023; Kohler & Puzrin, 2022; Kohler et al., 2021, 2022).

3.1 Material Point Method

The Material Point Method (MPM) is a numerical technique used in computational mechanics to simulate material behaviour under a very wide range of deformations (Sulsky et al., 1994). The domain to be modelled is discretised by Lagrangian particles (so-called material points) to track mass, momentum, deformation and constitutive state variables (see Figure 3.1). In order to solve Newton's law of motion, an Eulerian background grid is introduced which allows for the computation of the derivatives needed for the stress-based force evaluation.

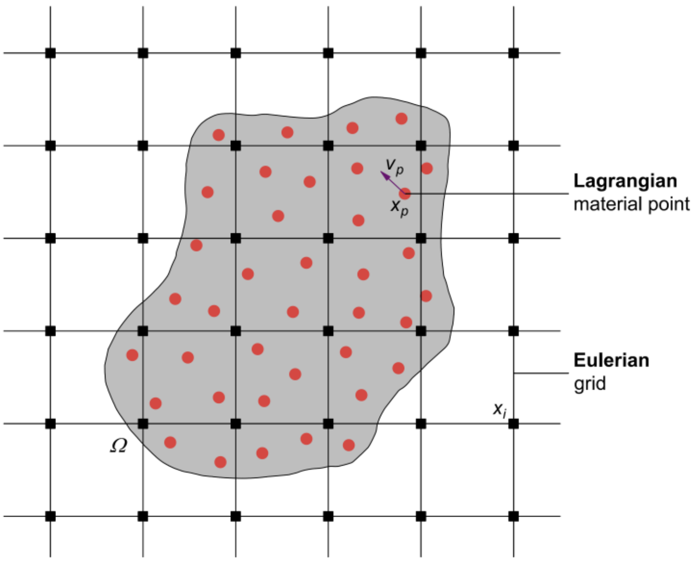

Figure 3.1: Lagrangian MPM discretization of a continuum and the Eulerian computational grid.

Initially, each material point is assigned a position $\boldsymbol{x}_p = (x_p, y_p)$, volume V_p and mass m_p. All the other quantities (i.e. velocity $\boldsymbol{v}_p$, deformation gradient $\boldsymbol{F}_p$ and Cauchy stress tensor $\boldsymbol{\sigma}_p$) are set to zero. Following the initialization, the motion of the material points is computed, based on the basic 4-step MPM algorithm (see Figure 3.2). Rather than using existing codes, an in-house MPM framework has been implemented in C++. This provides the required flexibility to implement the seismic boundary conditions and the necessary adaptions for performing seismic response analyses. The general implementation closely follows Stomakhin et al. (2013) and Jiang et al. (2015), using explicit time integration. For implementation details and main equations, the reader is referred to Kohler et al. (2021).

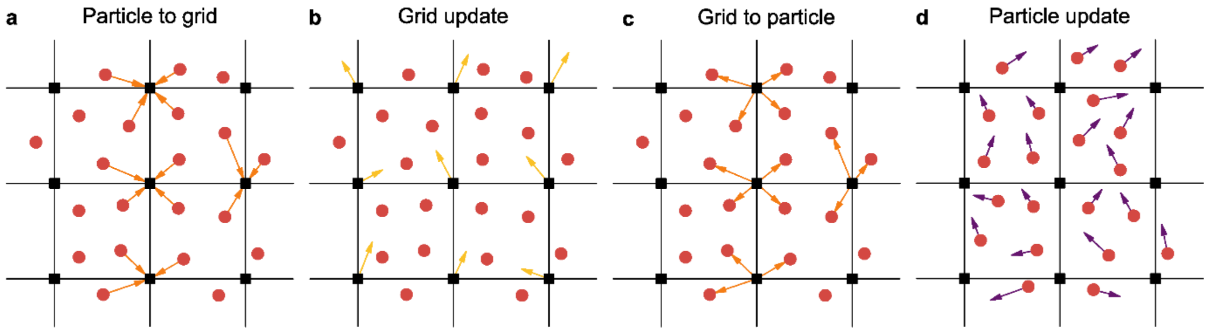

Figure 3.2: General 4-step algorithm of the MPM: (a) transfer of mass, linear momentum and forces from the material points to the grid, (b) solving the equation of motion on the grid, (c) transfer the updated grid velocities back to the material points and (d) evolve the material points and updated the deformation and stress state (after Soga et al., 2016).

3.2 MPM landslide model

The basis for modelling the seismic response of landslides is the MPM framework proposed by Kohler et al. (2021), where the implementation of appropriate boundary conditions for the seismic model is presented. Figure 3.3 shows an example of a 2D landslide model based on the Marsc landslide at the Luzzone reservoir. The application of MPM allows a geotechnical model of a landslide to be represented with any level of details. For this purpose, each material point can be assigned an arbitrary constitutive model with corresponding parameters. However, for the seismic boundary conditions to work optimally, the bottom and lateral boundaries of the model should be simulated with an elastic material. Ideally, the underlying bedrock should be integrated into the model as elastic base anyway. The remain material, including the landslide mass, is usually modelled using a Mohr-Coulomb yield criterion with friction angle φ and cohesion c. Depending on the type of soil or rock and the loading history, some softening or hardening must be included to properly represented the expected material behaviour. However, also more sophisticated constitutive models can be applied (e.g. to account for cyclic liquefaction). In case seismic wave profiles are available from geophysical testing, depth dependent compressional and shear wave velocity should be used. The reservoir is also included in the model by discretizing the water with material points. More details on the creation of an appropriate model and the selection of constitutive model can be found for two different case studies in Kohler & Puzrin (2022) and (Kohler, Hodel et al., 2023).

The seismic response of slopes is modelled in two main steps. First, the static stress field within the slope is computed using kinematic boundary conditions. In a second step, the actual seismic simulation is performed by applying the concept of a compliant base (Lysmer & Kuhlemeyer, 1969) and free-field columns (Wolf, 1989; Zienkiewicz et al., 1989). In order to model the existing landslide, the shear zone is pre-defined by assigning the corresponding material points to a different constitutive model (see Figure 3.3). The thickness of the shear zone δ_s has to be chosen based on the span of the interpolation functions to allow the material points to move accordingly. Except for very small landslides, it is not reasonable to match the numerical shear band thickness to the in-situ zone of intensive shearing, as a very small grid size would be needed. The computational cost would be rather high, owing to the small stable time increment and the large number of material points in the case of a regular grid. However, the numerical thickness has to be taken into account for the constitutive model, and an appropriate scaling approach has to be applied. Therefore, the smeared crack approach introduced by Rots et al. (1985) is also applied in MPM (Kohler et al., 2021; Soga et al., 2016; Yerro, 2015).

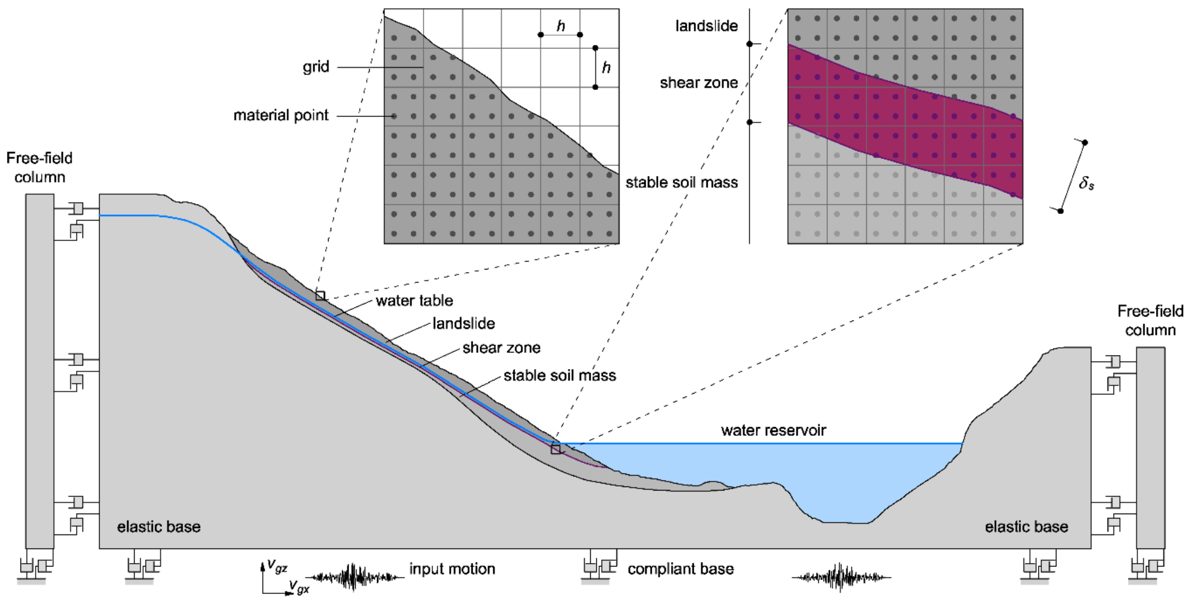

Figure 3.3: MPM landslide model. Schematic view of the MPM model of the landslide based on the Marsc landslide at the Luzzone reservoir, including the free-field columns at the lateral boundaries. The grid size is denoted with h and the thickness of the shear zone with δ_s. The earthquake motion is applied by a vertical and horizontal component denoted with ground velocities v_{gz} and v_{gx}.

The behaviour of slow moving landslides is often assumed to be controlled by the rate dependency in the shear zone and enables its state of constantly moving (Alvarado et al., 2019; Corominas et al., 2005; Li et al., 2023; van Asch et al., 2007). A positive rate effect in the shear zone allows the landslide to counteract a rise in the groundwater level by an increased velocity. This can even prevent landslides from catastrophically collapsing during extreme events such as heavy rain and earthquakes. Therefore, the shear zone is simulated by a viscoplastic material model, where the friction is introduced as a logarithmic function of the rate of the deviatoric plastic strain $\dot{\alpha}$

$$\tan\varphi = \tan\varphi_0 \left(1 + A \cdot \ln\left(\frac{\dot{\alpha} + \dot{\alpha}_0}{\dot{\alpha}_0}\right)\right) \tag{3.1}$$

where φ_0, A and $\dot{\alpha}_0$ are material parameters. This kind of relation is often chosen for clayey shear zones in active landslides (Alonso et al., 2016; Puzrin & Schmid, 2011; Wedage et al., 1998), but the reference rate $\dot{\alpha}_0$ is also added in the numerator to avoid the singularity in the logarithm. The landslide velocity v can be linked to the rate of the equivalent plastic strain $\dot{\alpha}$ for a given shear zone thickness δ_s, assuming simple shear conditions, as

$$\dot{\alpha} = \frac{v}{\sqrt{3}\delta_s} \tag{3.2}$$

The same relation can also be applied to link the reference landslide velocity v_0 to the reference strain rate $\dot{\alpha}_0$. It has been shown that the straightforward extension of small-strain models to finite strains based on rate form equations leads to various inconsistencies, such as spurious stress oscillations or improper energy dissipation (Bažant et al., 2012; Perić et al., 1992; Simo & Pister, 1984). Therefore, an appropriate large strain implementation for such a viscoplastic model for the shear zone is necessary and is presented in full detail in Kohler & Puzrin (2022).

3.3 Calibration of the shear zone model

For an accurate simulation of the landslide during earthquake shaking, the behaviour of the shear zone is crucial. Throughout the period before, during and after the earthquake, the shearing velocity can vary by several orders of magnitude. Ideally, the behaviour of the shear zone is calibrated over the entire expected range, which requires both time-resolved field measurements and laboratory tests.

3.3.1 Calibration using field data

The mechanical properties of the shear zone can be back-calculated from field displacement and pore water pressure measurements. This procedure is demonstrated using the example of the Marsc landslide at the Luzzone reservoir. Since the food of the landslide is partially submerged, the level of the reservoir needs to be taken into account as well. The evolution of the ground water level in the slope (derived from pore water pressure measurements), the landslide velocity (derived from SAA displacement measurements) and the level of the reservoir are presented in Figure 3.4. The direct relationship between groundwater and reservoir levels and landslide velocity is clearly evident.

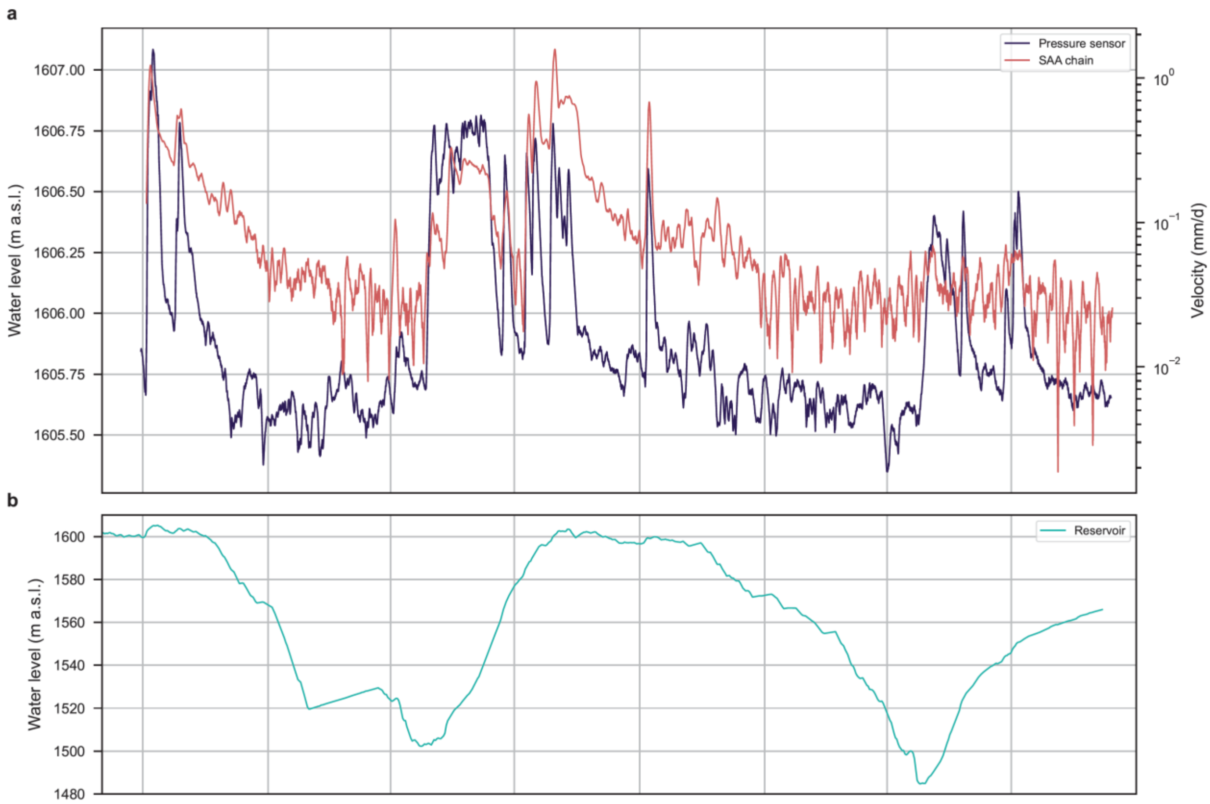

Figure 3.4: Measurements from Marsc landslide at the Luzzone reservoir. (a) Water level in the landslide and the landslide velocity from SAA chain and (b) reservoir level.

From the measurement data, different points in time can be selected and analysed using the strength-reduction method. Each of these scenarios then provides a critical friction angle that is required to achieve exactly a safety factor of one. Assuming that the rate dependency in the shear zone is the cause of this variation in strength, the determined critical friction angle for each scenario can be plotted against the corresponding landslide velocity (see Figure 3.5). It can be seen that with a semi-logarithmic representation there is indeed a correlation according to equation (3.1) and thus allows for such a calibration of the rate dependency. It should be noted that this calibration only covers the observed range of landslide velocities. While this procedure allows for reliable simulation of the landslide at velocities in the annually observed range, during an earthquake significantly higher velocities can be expected. Therefore, additional laboratory tests should be carried out to investigate the behaviour of the shear zone at higher velocities.

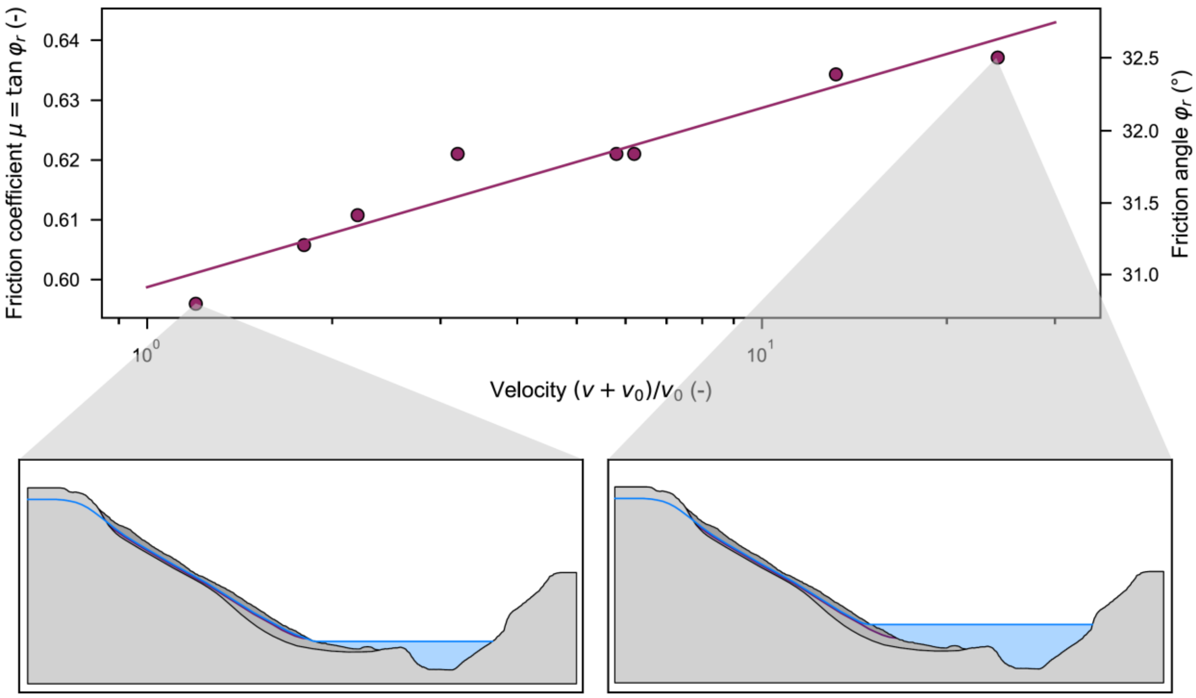

Figure 3.5: Calibration of the rate dependency in the shear zone using field measurements and the strength reduction method.

3.3.2 Calibration using lab data

The shear behaviour of soils at large displacement (e.g. landslide shear zones) can be investigated by performing ring shear tests. The ring shear apparatus was initially proposed to measure the residual friction angle in shear zones at very slow speeds (Cooling & Smith, 1936; Gruner & Haefeli, 1934; Hvorslev, 1939). A ring-shaped soil sample is therefore first loaded vertically until the desired normal stress is reached and then rotated to apply the target shear velocity. There exist different types of ring shear apparatus, but the so-called Bishop-type device is usually preferred (Bishop et al., 1971). This device consists of upper and lower confinement rings with a controllable gap in between. By rotating the lower rings while simultaneously holding the upper rings in place, the shear plane is forced to develop at this gap. The shearing at different velocities allow to investigate the rate dependency of the shear strength (Lemos, 2004; Lemos & Vaughan, 2000; Tika et al., 1996). A major disadvantage of the Bishop-type apparatus is the extrusion of soil through the gap between the confinement rings, which becomes even worse at higher shear speeds. It is not clear how this constant leakage of soil influences the observed shear behaviour. Furthermore, the gap leads to an immediate dissipation of potential excess pore water pressures developed during shearing. This might not only affect the shear resistance but also makes it pointless to measure pore water pressures directly at the shear zone. This issues have been overcome by a series of undrained ring-shear devices developed in the last decades (Sassa, 1984, 1996; Sassa et al., 2004). The central improvement is a rubber edge placed between the lower and upper rings as sealing to prevent leakage of both water and soil. This allowed Sassa et al. (2004) to study the undrained shear behaviour of different soils and investigate the soil liquefaction by means of ring shear tests.

This ring shear design has been further improved by optimising the sealing between the confinement rings using PTFE (polytetrafluoroethylene) seals (Figure 3.6 and 3.7). PTFE has the advantage of a very low friction coefficient and in particular exhibits an exceptionally steady frictional behaviour over very large shear deformations. This enables an accurate measurement of rate effects during shearing. Further details on the apparatus and results on rate effects in landslide shear zones can be found in (Kohler, Hottiger et al., 2023).

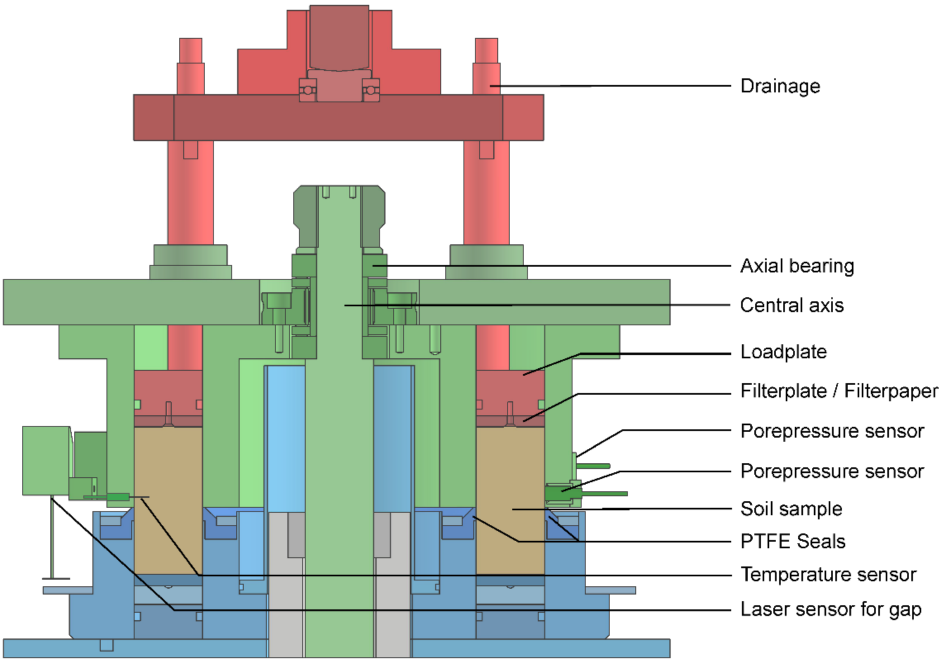

Figure 3.6: Cross section of the ring shear box showing all the main parts and sensors.

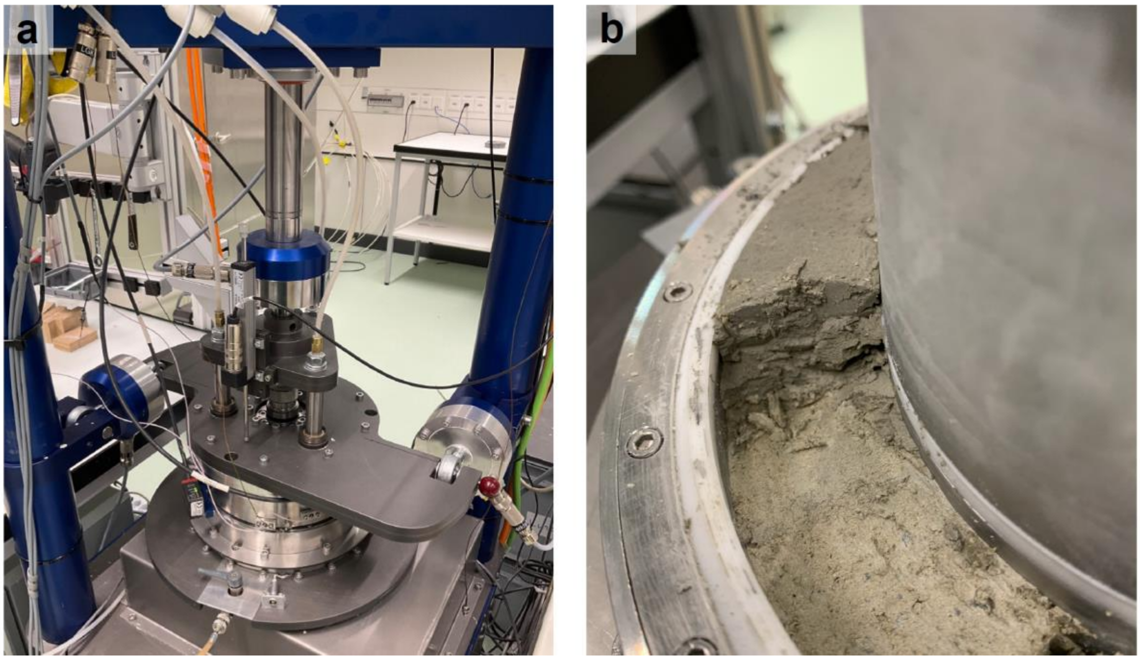

Figure 3.7: Photos of the ring shear apparatus (a) and the shear zone and PTFE seals (b).

In order to investigate the behaviour of the Marsc landslide, samples were retrieved from the shear zone and testing using this ring shear apparatus. The resulting slow residual friction angle at a velocity of 0.01 mm/min from different samples lies in the range of $\varphi_r = 24° \pm 1$, which is well below the minimum required value based on the strength-reduction analysis of the most stable scenario. Such a discrepancy between field and laboratory is a common problem and can have various causes (Corominas et al., 2005; van Asch et al., 2007). In this case, one of the main reasons is that only the fraction smaller than 2 mm could be tested in the ring shear apparatus, leaving gravel size particles constituting approximately 20% of material by weight excluded. In addition, the shear surface is modelled as smooth, but in reality it is rather an irregular surface, deviating around cobbles and blocks. Given the inhomogeneous structure of the landslide, it must also be questioned how representative local conditions are for the entire landslide. For this reason, the results of the ring shear tests cannot be directly transferred to the landslide model. Nevertheless, the ring shear tests are very important because they allow the behaviour of the shear zone to be studied at much higher speeds, which are not observed during the annual movements. Different test protocols covering a wide range of velocities have thus been conducted on the shear zone samples. The results clearly show a rate hardening behaviour (Figure 3.8a). By normalising the friction with the corresponding slow residual friction coefficient μ_0, the rate dependency obtained from laboratory tests can be compared to the one back-calculated from the field measurements (Figure 3.8b). Despite the clear difference in shearing velocity, a similar trend of the rate hardening can be observed. In fact, the rate dependency parameter of $A = 0.03$ obtained by a regression of the ring shear results is only slightly higher than the value $A = 0.02$ based on the field observations.

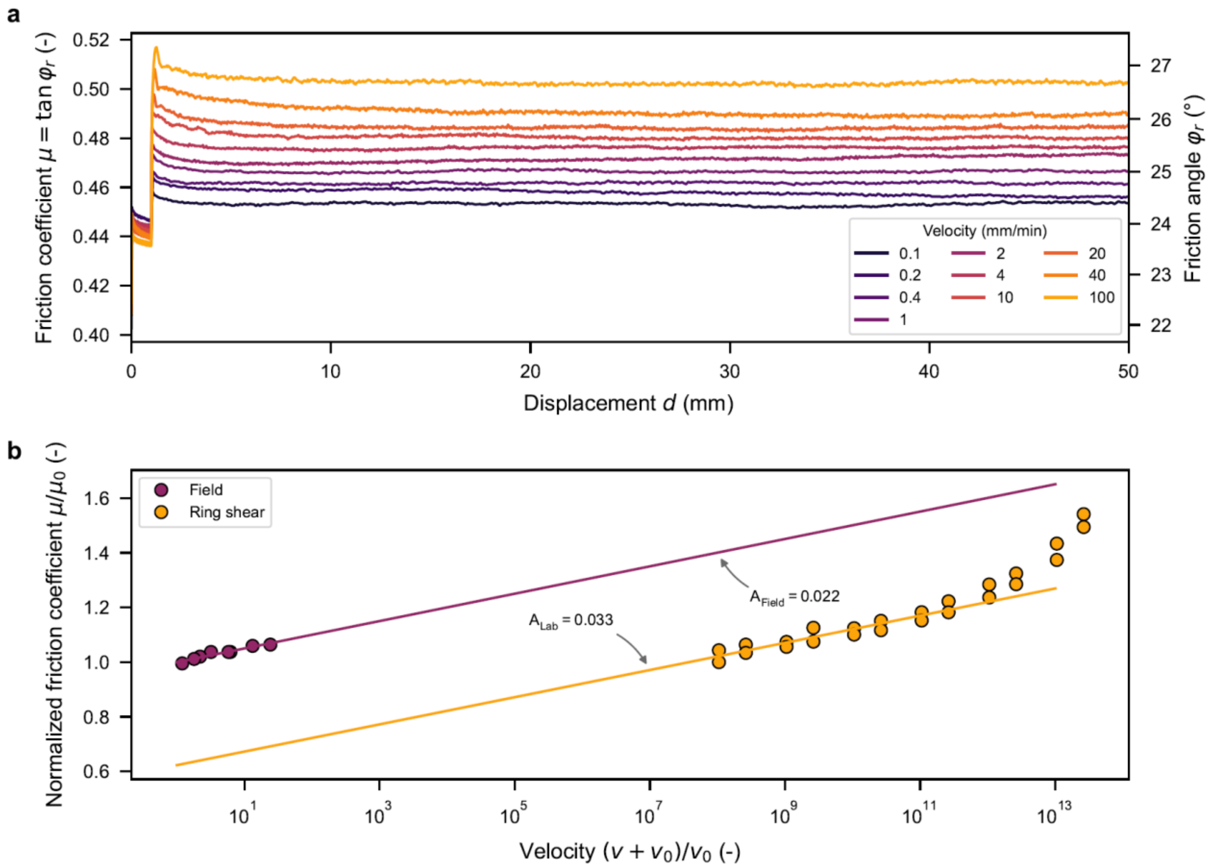

Figure 3.8: Ring shear tests results on samples from the shear zone of the Marsc landslide at different shearing velocities (a). Comparison of the rate dependency derived from field observations and lab testing (b). The ring shear test results from the three highest velocities are not considered for the regression to not overestimate the rate dependency at lower velocities.

3.4 Simulation results

3.4.1 Co-seismic displacements

The calibrated MPM landslide model (Figure 3.3) is subjected to a set of strong motions, which were retrieved from the ESM database (Luzi et al., 2020). The seismic stations are classified as ground type A according to Eurocode 8 (Comité Européen de Normalisation, 2004) and are thus suitable as input on the elastic base. To investigate the influence of the shear zone behaviour, a parametric study is performed by varying the rate dependency parameter in the range of $A = 0.01 - 0.03$, around the values observed in field and lab measurements. In addition, also a rate independent case ($A = 0$) with a safety factor of $SF = 1.01$ is included in the simulation for a comparison. The resulting co-seismic displacements are presented in Figure 3.9. Similar to the results of a traditional Newmark's sliding block analysis, the displacements increase stepwise with the impulses of the ground motion. Once the main part of the earthquake has passed, the displacement does not seem to further increase. However, this is only true for the rate independent case, where the landslide returns to a stable state. For the rate dependent case, the landslide regains the pre-seismic state of slow motion, which is not visible in Figure 3.9 due to the time scale.

An identical pattern can be observed for all earthquakes, where the rate independent case leads to the largest displacements. As expected, an increase in rate dependency parameter A has the effect of reducing the co-seismic displacements. Considering the mobile quasi-static pre-seismic state of the landslide, the predicted motion of the landslide is surprisingly low, even without any rate dependency in the shear zone. As already suggested in other studies (Jibson, 2007; Keefer, 2002), the Arias intensity is the preferred seismic parameter to investigate effects of earthquakes on the landslide displacements. The summary of the results (Figure 3.9f) shows a direct correlation between the final displacements and the Arias intensity for a rate independent shear zone. The same can be observed in case of only low rate dependency ($A = 0.01$), where as for the other cases the trend is not that conclusive.

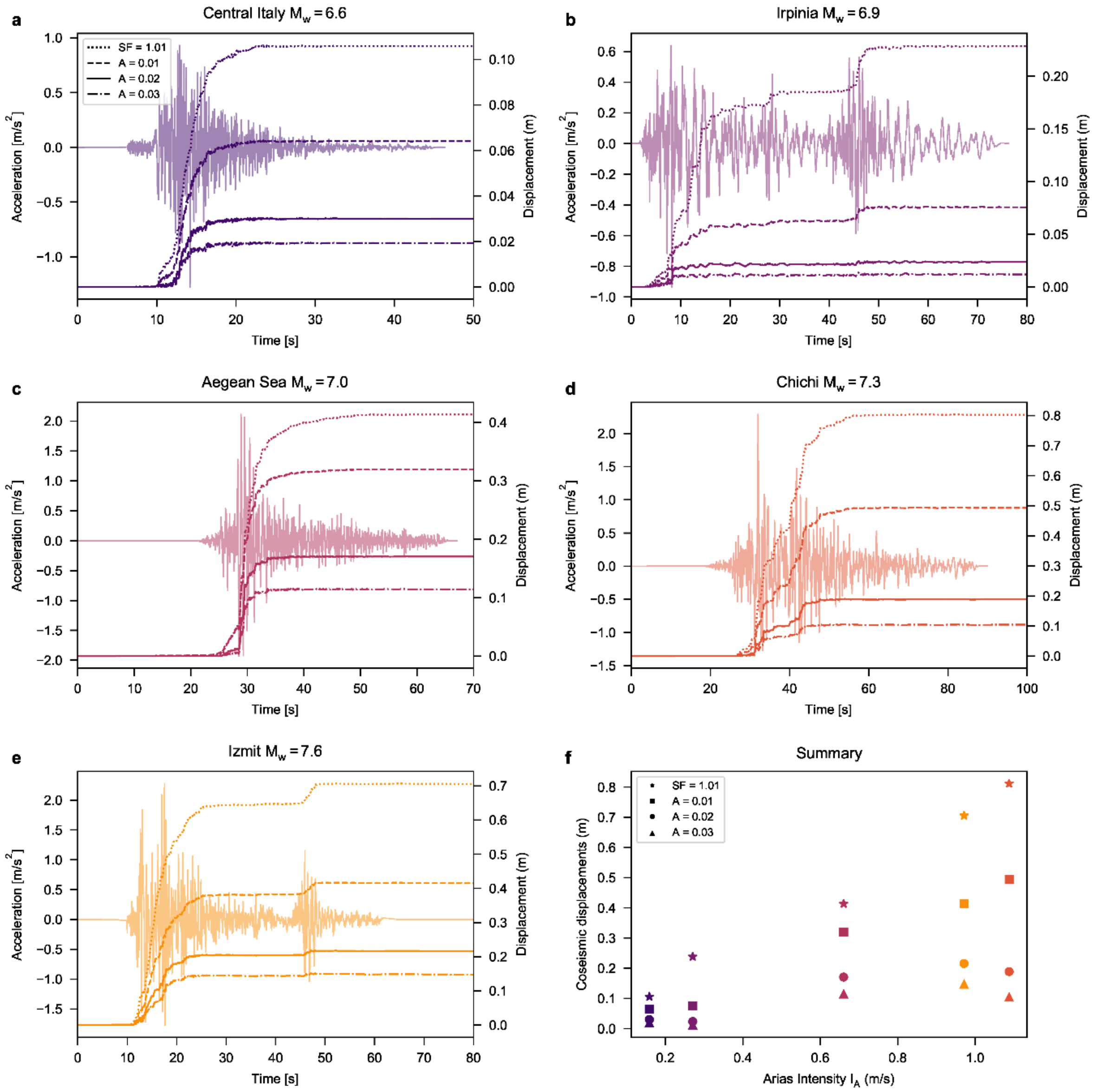

Figure 3.9: Results from parametric study. Ground acceleration and evolution of co-seismic displacements calculated at the bottom of the landslide for different earthquake events (a-e). The simulations are performed each for a rate independent shear zone and for three different rate dependency parameter A. Summary plot showing the final co-seismic displacements against the corresponding Arias intensity (f). Reprinted from Kohler et. al. (2023), where further information can be found.

3.4.2 Pessimistic scenarios

The preceding simulations have shown that even when rate dependency is neglected, only moderate co-seismic displacements are to be expected. For this reason, the corresponding wave heights in the reservoir were not evaluated, as they are negligibly small. Based on the field and laboratory measurements, it can be assumed that these are realistic scenarios for the actual behaviour during a potential earthquake. However, there might be other effects, which have not been considered so far and could cause a catastrophic response. These are, on the one hand, a potential softening in the landslide body (Kohler & Puzrin, 2022) and, on the other hand, a strength reduction in the shear zone due to excess pore pressures as a consequence of cycling loading (Kohler & Puzrin, 2023). Other potential factors reducing strength include frictional heating (Alonso et al., 2016; Vardoulakis, 2002) and other reasons for negative rate effects (Tika et al., 1996). In order to assess these scenarios, additional simulations are performed where a softening of the landslides mass from the peak values φ, c to the residual values φ_r, c_r and a rate softening in the shear zone ($A < 0$) are included. Due to the introduction of negative rate dependency, the initial safety factor $SF = 1.1$ is assumed, which does not represent an active state of the landslide, but is necessary to keep it in an equilibrium state before the earthquake.

The results of the simulations are presented in Figure 3.10. The evolution of displacements (Figure 3.10a) shows that a small negative rate effect, even when combined with a softening in the landslide mass, does only slightly increase the landslide displacements compared to the rate independent case. Assuming a strong negative rate effect ($A = -0.01$), the landslide starts accelerating even before the earthquake and thus is in an initially unstable state. When this is combined with the softening of the landslide mass, a considerably larger acceleration occurs. This is illustrated by the corresponding landslide velocity and mobilized friction coefficient in the shear zone (Figure 3.10b). The earthquake in this case has only a marginal influence on the landslide. It should be emphasized that the landslide does not reach a stable state at the end, but exhibits an unstable stick-slip behaviour and continues to move at a velocity of about 1 m per day. The spatial distribution of displacements (Figure 3.10c, d) and velocities (Figure 3.10e, f) shows that the landslide initially moves as a coherent body. However, the final displacements reveal that two new shear surfaces were formed due to the softening in the landslide mass. While the upper part experienced larger displacements, the submerged foot of the landslide moved less, due to resistance of the reservoir. The evolution of the vertical displacement of different points on the water surface allows an estimation of the wave height in the reservoir (Figure 3.10g). The highest wave of about half a meter occurs on by breaking on the steep opposite rock flank. The freeboard of the reservoir exceeds this wave height by far and thus an overtopping seems unlikely based on this simulation.

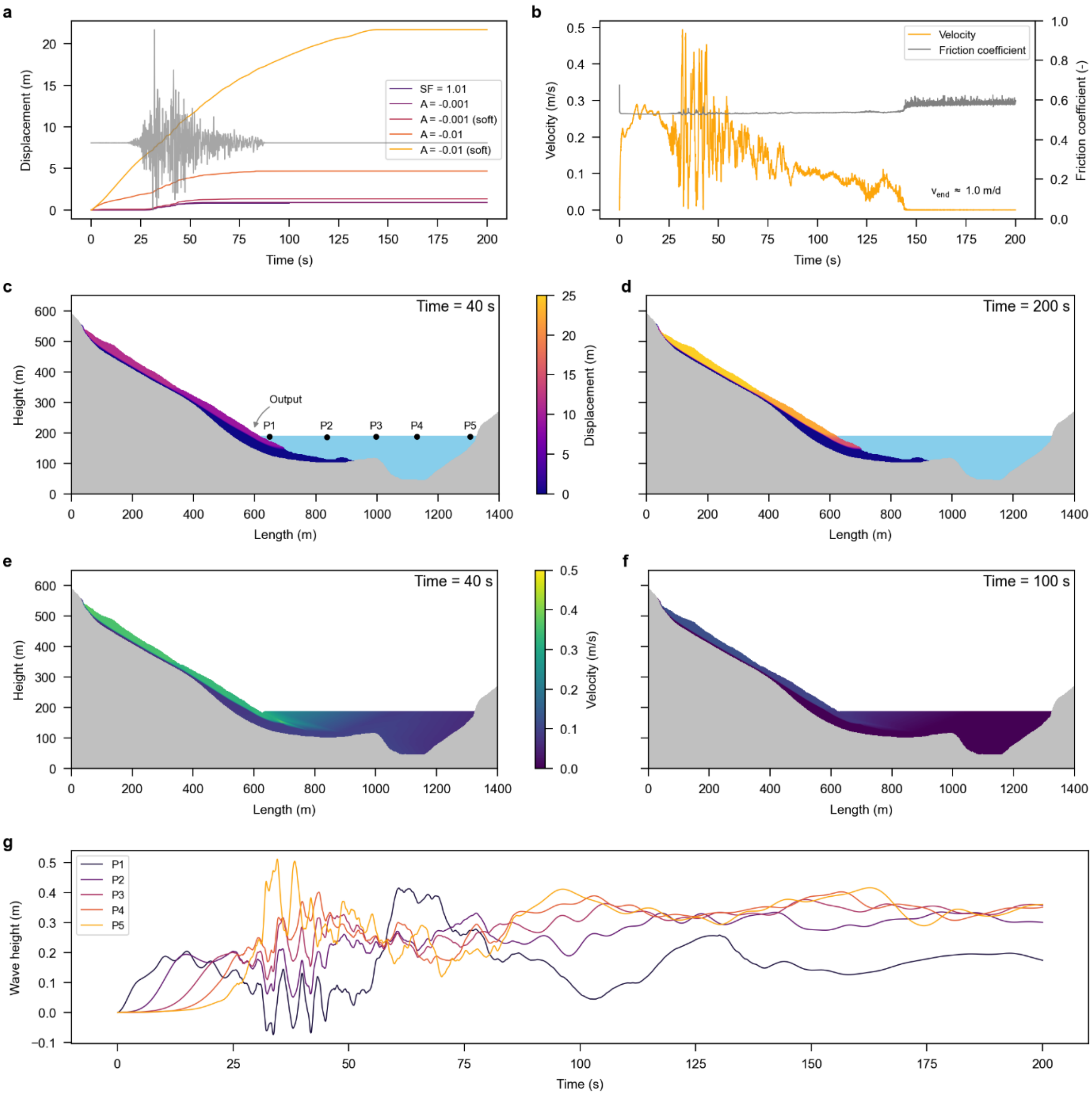

Figure 3.10: Results from the pessimistic simulation. Earthquake acceleration and evolution of landslide displacements at the bottom (marked in c) for different scenarios, where "soft" referrers to the softening in the landslide mass (a). Landslide velocity and mobilized friction coefficient in the shear zone for the worst scenario (b). Spatial distribution of displacements (c and d) and velocities (e and f). Wave height for the worst scenario at different locations (marked in c) along the water surface (g). The applied ground motion is from the Chichi earthquake. Reprinted from Kohler et. al. (2023), where further information can be found.

3.5 Discussion

3.5.1 Co-seismic displacements

Considering the mobile quasi-static state of an active landslide, large co-seismic displacements can be expected and would also be predicted by a classical Newmark type analysis. Nevertheless, the simulations presented here show rather small displacements, even for a strong earthquake and even after neglecting the rate hardening effect. Similar results have been found in other studies (Kohler & Puzrin, 2022; Pinyol et al., 2022), which highlights the importance of the model representing the actual kinematics of a landslide. Observations of real landslides confirm these numerical results. For example, La Sorbella landslide shows co-seismic displacements of less than 1 mm during three earthquakes of the central Italy sequence (Ruggeri et al., 2020). The Maca landslide in Peru also moved only a few centimetres during two earthquakes (Bontemps et al., 2020; Lacroix et al., 2014). Similar observations were made for numerous landslides during the strong Sarpol-e-Zahab (Iran) and Gorkha (Nepal) earthquakes using remote sensing techniques (e.g. InSAR), with only one showing a displacement greater than one meter (Cheaib et al., 2022; Lacroix et al., 2022).

The observations and simulations suggest that active landslides are significantly less susceptible to earthquakes than previously thought and a rather moderate response can be expected. This finding is supported by the fact that most of these landslides are rather old and thus likely to have withstood various extreme events such as strong earthquakes or heavy rainfalls. In addition, these often are the remains of historical catastrophic landslide events and processes involving large strength losses have already been completed. This is especially true for the Marsc landslide and the presented scenario with significant softening of landslide mass can be considered very unlikely. Based on the ring shear tests, negative rate effects in the shear zone can also be excluded. On the contrary, the experimental results indicate a larger increase in shear resistance at very high velocities, which was neglected in the presented simulations. It should also be pointed out that the introduction of a negative rate dependency over the entire velocity range requires a pre-seismic state with a safety factors higher than one. The usually observed slow movements controlled by hydrology (e.g. Carlà et al., 2021; Pinyol et al., 2022) would not be possible under such conditions.

3.5.2 Catastrophic collapse

Despite the expected small co-seismic displacements and the rather unlikely scenario of a catastrophic collapse, it is important to also include pessimistic scenarios given the potential consequences for a water reservoir and the valley below. This is emphasized by the event of Vajont (Hendron & Patton, 1987) and other landslides showing a transition from slow-moving to a fast acceleration (Carlà et al., 2019; Handwerger et al., 2019; Intrieri et al., 2018). However, the scenarios simulated here show that, even under these pessimistic assumptions, no severe consequences are expected for the Marsc landslide. Although negative rate effects have been observed in laboratory tests on different soils (Tika et al., 1996), they have not been confirmed in the ring shear tests on the Marsc landslide material. The residual strength of the landslide mass was assumed to be equal to the value, which was back-calculated for the shear zone. This is a rather conservative assumption for the gravelly stratigraphy.

A major difference of the catastrophic events is that these are often characterised by rather brittle material behaviour due to the presence of rock. A similarly brittle behaviour is found in soil slopes primarily during first-time failure, where mechanisms such as strain softening (Skempton, 1985) or cyclic excess pressures (Kramer, 1996) are dominant. These effects are one of the main reasons for the seismic triggering of debris flows and are often observed during strong earthquakes (Rodríguez et al., 1999). A striking example of a catastrophic collapse triggered by an earthquake is the Tsaoling landslide in Taiwan (Chigira et al., 2003; Tang et al., 2009). Although not in the category of slow-moving landslides, the Tsaoling landslide was an active landslide with several rock fall and debris flow events before the Chichi earthquake in 1999. Due to the flexibility of MPM, the presented methodology can readily be extended to any type of active landslides, regardless whether they consist of soil, rock or a mixture. This allows the characteristics of each individual case to be represented and possible scenarios to be simulated. The application to the Tsaoling landslide using the same approach is presented in Figure 3.11. It can be observed, that the landslide was triggered at the peak impulse of the earthquake and well agrees with alternative simulations and survivor's witness (Togo et al., 2014; Yang et al., 2014). In contrast to simplified methods, MPM enables the following simulation of the landslide's runout and is in good agreement with observations (Chen et al., 2006; Kuo et al., 2009). Further details of the model and results can be found in Kohler et al. (2022). The main reasons for this catastrophic failure are, on the one hand, the brittle behaviour of the sliding mass, which consists mainly of rock, and on the other hand, a pronounced softening of the fault gauge (Mizoguchi et al., 2007).

An old slow-moving landslide that has probably experienced several extreme events during its life, behaves much more ductile and is less likely to fail suddenly. As the case of Vajont shows, caution is required when the hydro-mechanical condition of a landslide is significantly disturbed (e.g., by filling of the reservoir). Although, the Marsc landslide is strongly influenced by the reservoir, the history and the continuous monitoring has shown that this lies well within an acceptable range. This is confirmed by the Three Gorges Project in China, where it was found that the risk of catastrophic landslide events was mainly concentrated to the period of filling the reservoir (Yin et al., 2016). Furthermore, the Vajont landslide is characterized by rather different geological conditions of a rockslide and a thin, clayey basal sliding surface (Paronuzzi et al., 2021), which is believed to have caused the collapse due to frictional heating (Alonso et al., 2016; Vardoulakis, 2002).

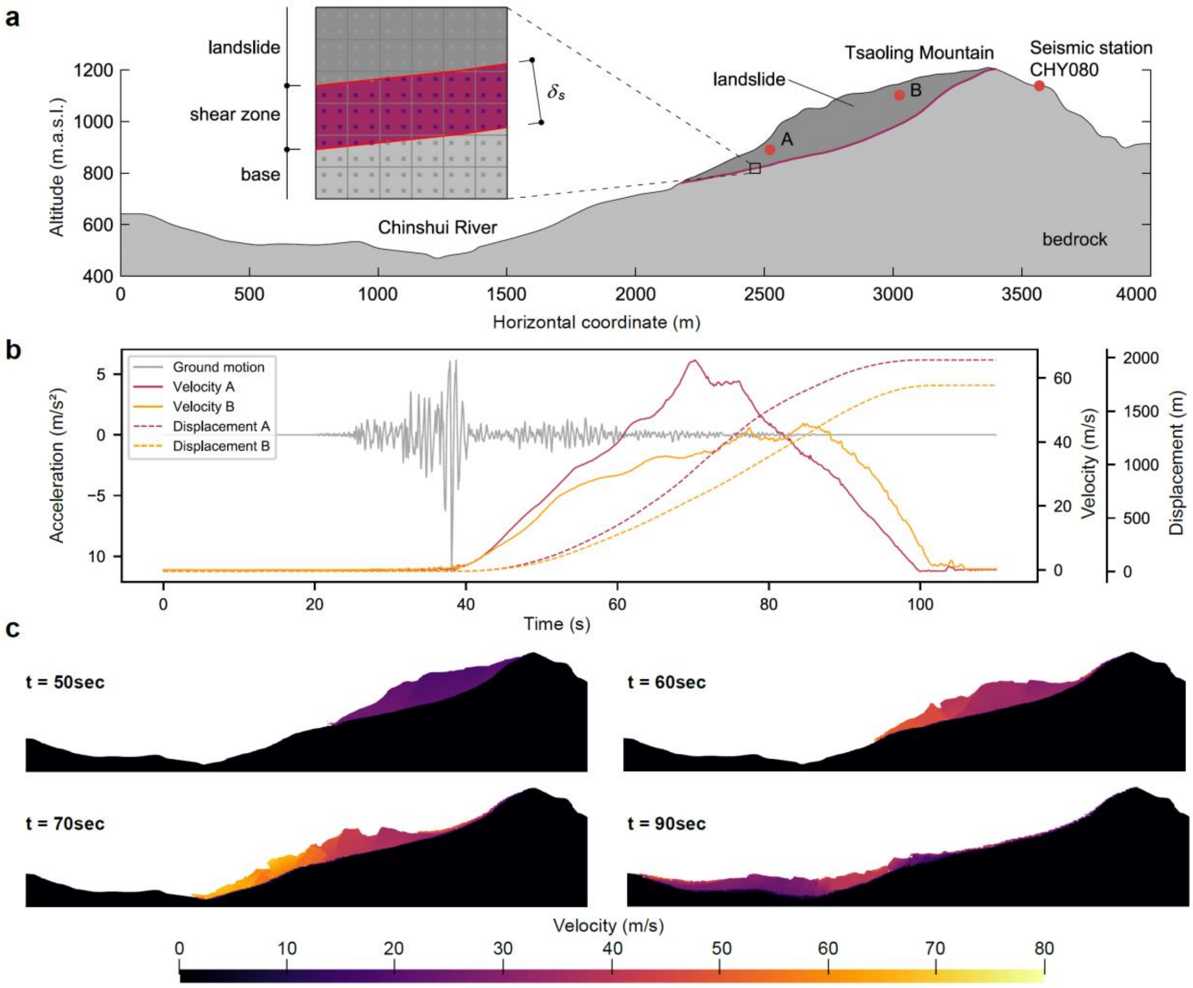

Figure 3.11: Simulation of the catastrophic Tsaoling landslide. Cross section of the landslide model including the selected output points (after Tang et al. (2009)) (a). Evolution of velocities and displacements of two selected points in the landslide (b). Displacements and velocity distribution at selected times during the landslide failure (c).

4 Post-seismic behaviour of active landslides

The often observed phenomenon of increased landslide activity after an earthquake (Bontemps et al., 2020; Lacroix et al., 2022; Marc et al., 2015; Song et al., 2022) is discussed in this chapter. In recent year, the most common mentioned explanation lies in the generation of excess pore water pressures (PWP) due to cyclic earthquake loading outside of the shear zone, which later propagate into the shear zone leading to an increase landslide velocity. This mechanism is investigated using a coupled hydro-mechanical approach. The model and the most important results are presented in the following. This chapter is based on the published article Kohler & Puzrin (2023).

4.1 Landslide model

In order to investigate the hydro-mechanical behaviour of active landslides during earthquakes, we propose a simplified model assuming infinite slope conditions (Figure 4.1). The landslide is reduced to slope parallel layers including a base, stable soil and landslide mass, where the latter are separated by the shear zone. The local stratigraphy can be accurately represented by splitting the soil above and below the shear zone into a number of sublayers with different constitutive models and parameters. The landslide model is based on the theory of saturated porous solids und dynamic conditions introduced by Biot (1956, 1962), which is solved using a finite element discretization. This represents a unified framework, where the mechanism of seismic wave propagation, landslide movements and PWP dissipation are included. However, to get an accurate representation of the landslide behaviour it is crucial to select appropriate constitutive models for the shear zone and the adjacent soil.

The shear zone is assumed to have experienced a long history of localized shearing and therefore remains in the critical state, where no or only negligible excess pressure will be generated (Lemos, 2004; Schulz & Wang, 2014; Skempton, 1985) during seismic loading. To model shearing rates over several orders of magnitudes during the pre-, co- and post-seismic periods of landslide evolution, the same logarithmic rate-hardening friction law (equation 3.1) is applied as for the co-seismic MPM simulation.

Adjacent to the shear zone, above and below it, two identical layers of fine-grained soils of relatively low permeability are assumed. As pointed out in the introduction, these soils have not yet reached the critical state and, therefore, can experience an accumulation of excess PWP along with the stiffness and strength degradation (Boulanger & Idriss, 2004; Kramer, 1996). Therefore, a multi-surface plasticity model following the framework developed by Prevost (1985) is applied in this work. The basic idea is that for each yield surface the volumetric behaviour is defined to control whether the soil shows a contractive or dilative behaviour. In case of undrained cyclic loading during earthquake shaking, this can result in generation of excess PWP depending on the stress amplitudes and number of cycles. It should be emphasized that the adjacent layers can be interpreted either as homogenous or as homogenized sequence of different sublayers, representing soil susceptible to the generation of excess PWP near the shear zone. The shear zone is likely to be less permeable than the adjacent layers due to its compacted state (Comegna et al., 2007). There is, however, some field evidence showing that it can also be more permeable (Di Maio et al., 2020). In this study they are modelled with the same permeability, which allows for reduction in the number of model parameters. This simplification is justified because the thickness of shear zones, typically ranging from millimeters to decimeters (Corominas et al., 2005; Miao & Wang, 2022; Oberender & Puzrin, 2016; van Asch et al., 2007), is orders of magnitude smaller than that to the adjacent layers. Consequently, the shear zone contribution to seepage is small and not sensitive to its permeability. The stable soil and the landslide mass above the adjacent layers are modelled as linear elastic with a considerably higher permeability and can, therefore, be seen as drainage layers. Whether this corresponds to the actual stratigraphy or whether, for example, this is just a layer of sand or gravel bounding the fine-graded soils is less relevant. Even if there are additional layers susceptible to the generation of excess PWP within the stable soil or the landslide mass, in reality they will hardly influence the shear zone since for landslides of finite lengths the drainage layers will predominantly dissipate excess PWP along the slope. This model should be seen as a generalization of typical landslide conditions (Hungr et al., 2014; Lacroix et al., 2020; Oberender & Puzrin, 2016; Zerathe et al., 2016) to investigate the underlying mechanism. More details on the landslide model, the applied constitutive models and the corresponding parameters can be found in Kohler & Puzrin (2023).

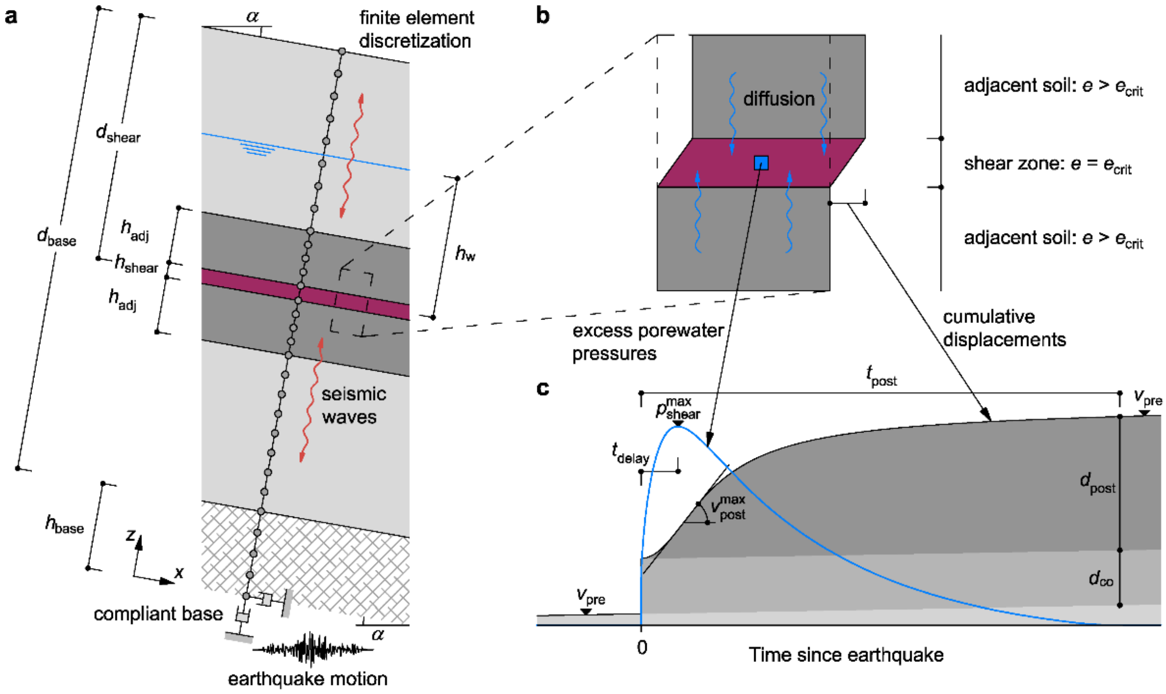

Figure 4.1: Landslide model. (a) The landslide model including the finite element discretization for displacements and pore pressures (considerably more elements are used in the simulations to have a proper representation). (b) Schematic representation of the diffusion of excess pore water pressure from the adjacent soil into the shear zone. The shear zone is assumed to have reached the critical state porosity e_{crit}, whereas the adjacent layers have a higher porosity. (c) Schematic representation of the seismic behaviour of landslides: Starting from an preseismic velocity v_{pre}, the landslide is hit by an earthquake leading to co-seismic displacements d_{co}. Excess pore water pressures generated in adjacent soil layers can propagate into the shear zone (blue curve) and lead to a post-seismic activity. Depending on the permeability and the thickness of the layers, this effect can last over a period t_{post} lasting from hours and days to several months. The maximal postseismic velocity v_{post}^{max} is achieved when the excess pore pressures in the shear zone reach the maximal value, which can be delayed by the time t_{delay}, while also depending on the permeability and thickness of the layers. Reprinted from Kohler & Puzrin (2023), where further information can be found.

4.2 Results

4.2.1 General results

An example simulation based on the Maca landslide (Zerathe et al., 2016) is presented in Figure 4.2. Rather different patterns can be observed for pre-, co- and post-seismic displacements (Fig. 4.2a). The initial state of slow movements is interrupted by a short period of distinct displacement steps induced by the earthquake (Fig. 4.2b). After the earthquake, the landslide shows a one day-long acceleration followed by a deceleration over several days reverting to the pre-seismic velocity. The generation of excess PWPs in the adjacent soil layers during the earthquake and the following diffusion into the shear zone are presented in Figures 4.2c and d, respectively. The spatial distribution of excess PWPs provides several important insights: (i) generation of excess PWPs is significantly reduced in the vicinity of the shear zone due to the smaller amplitude of shear stresses, limited by the residual shear strength in the shear zone; (ii) since no excess pressures are generated in the shear zone, the only source of their increase is the diffusion from the adjacent soil; (iii) the maximal excess PWP reached inside the shear zone is considerably smaller than those in the adjacent soil. The excess PWPs in the adjacent soil and the corresponding degradation of strength could theoretically lead to the formation of new shear zones. While the proposed mechanism can capture this effect automatically via the strain softening model used for the adjacent soil, it has not been observed in simulations due to the large difference between the residual strength of the shear zone and the peak strength of the adjacent soil.

The initial increase and the following dissipation of excess pressures in the shear zone can explain the observed post-seismic landslide acceleration and deceleration due to the associated reduction of effective stresses and hence change in the shear resistance. While the geometry, material parameters and seismic loading chosen for this demonstration example are realistic and produce a possible co- and post-seismic slope behaviour, this alone does not provide an insight into relative effects of individual parameters and corresponding mechanisms. Therefore, Kohler & Puzrin (2023) carried out an extensive parametric study and emphasized the analogy between the dissipation of excess pore water pressures from the adjacent soil layers and the one-dimensional consolidation theory (von Terzaghi, 1925). As a direct measure for the duration of the post-seismic period of increased landslide velocity they defined the characteristic consolidation time as

$$T_{char} = \frac{h^2 \gamma_w}{kM} \tag{4.1}$$

where $h = h_{adj}$ is the thickness, k the permeability, M the average constrained modulus of the adjacent layers and γ_w is the specific weight of water.

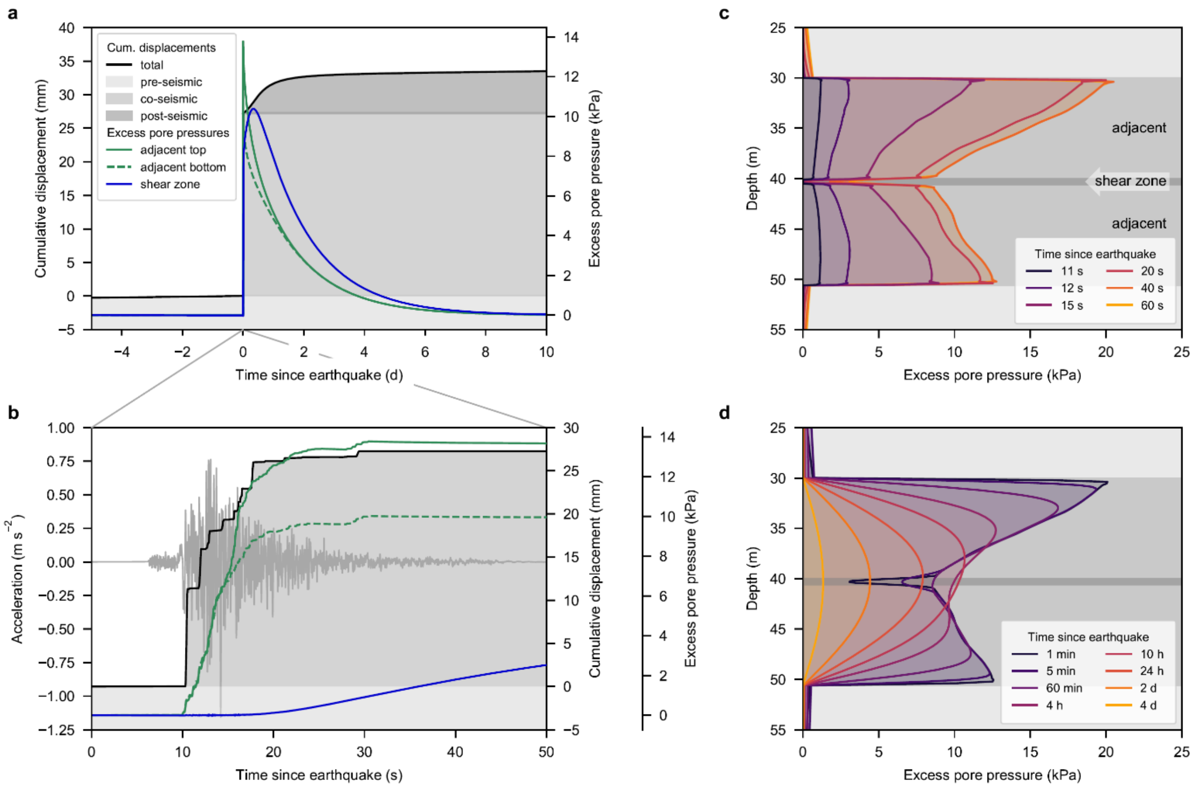

Figure 4.2: Example simulation. (a) Cumulative displacements split into pre-, co- and postseismic contributions and the evolution of excess pore water pressures in the shear zone and the adjacent layers (average). (b) Zoom of the co-seismic behaviour showing the input ground motion (Engineering Strong Motion (ESM) database signal ID: IT-MNF-EMSC-20161030_0000029-HE (Luzi et al., 2020)), cumulative displacements and the evolution of excess pore water pressures in the shear zone and the adjacent layers. (c) Generation of excess pore water pressures in the adjacent soil layers during the earthquake (shear zone marked in dark grey). (d) Dissipation of excess pore water pressures during the postseismic period (shear zone marked in dark grey). Reprinted from Kohler & Puzrin (2023), where further information can be found.

Similar to the co-seismic behaviour, rate dependency in the shear zone is a major factor influencing post-seismic activity. In general, the higher the rate dependency, the lower the post-seismic acceleration and displacement of the landslide. However, at very low rate dependencies this relation is more complicated due to the isolating effect of the shear zone and is discussed in detail by Kohler & Puzrin (2023). Furthermore, it was identified that the post-seismic landslide velocity directly correlate with the pre-seismic velocity. In the pre-seismic state, the equilibrium is maintained because the reduction in shear resistance caused by a precipitation-driven increase in PWP is counterbalanced by rate-hardening of the shear zone due to an increased landslide velocity. The post-seismic motion can be viewed as a perturbation of this pre-seismic state by a co-seismic increase in PWP, explaining this direct correlation. Finally, it was shown that the post-seismic motion clearly increase with increasing ground motion intensity. Amongst, the most popular intensity measures the peak ground velocity (PGV) was found to provide the best correlation. However, it has also been shown that two ground motions with similar PGV can lead to post-seismic displacements differing by several orders of magnitude.

4.2.2 Application to the Maca landslide

Located in a seismically active zone in Peru, the Maca landslide is in a persistent state of slow movements driven by rain and small earthquakes (Bontemps et al., 2020). In 2013, this region was hit by a shallow M_w 6.0 earthquake located 20 km away from the landslide. By means of a permanent GPS station, both the co- and post-seismic displacements could be recorded (Lacroix et al., 2014). The co-seismic displacements of around 20 mm were followed by a 30-day period of increased landslide velocity cumulating in additional 60 mm of post-seismic displacement. Kohler & Puzrin (2023) applied the presented approach to this case and have shown that the observed behaviour can be explained by the generation of excess PWP in adjacent layers of the shear zone (Figure 4.3).

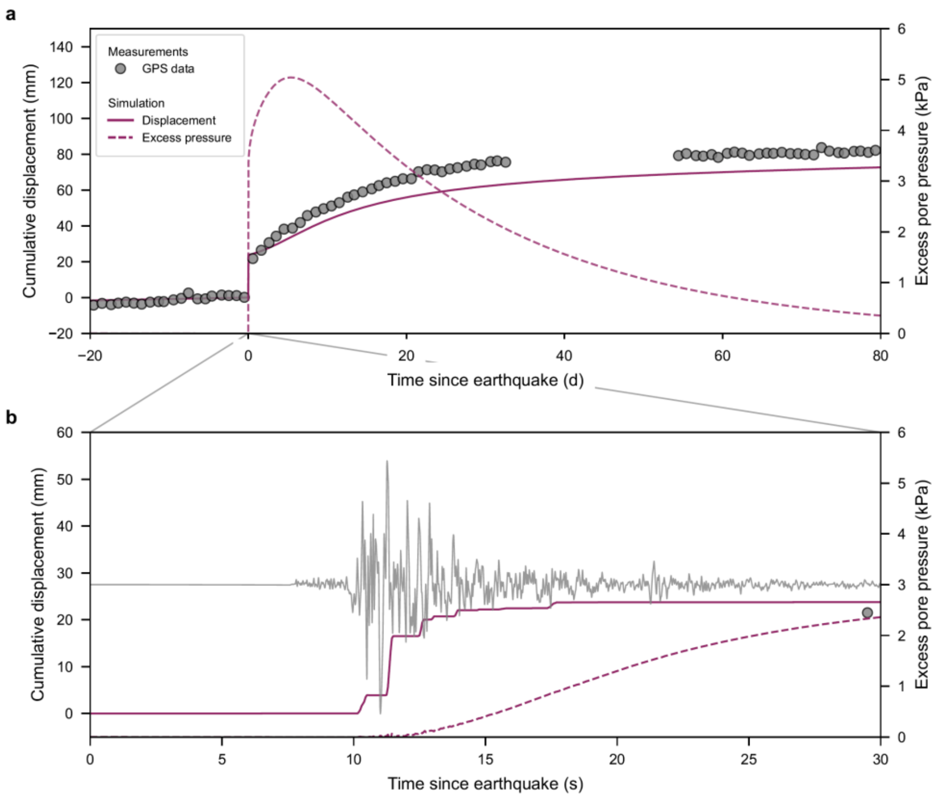

Figure 4.3: Application to the Maca landslide in Peru. (a) Comparison of the GPS measurements (adapted from Lacroix et al. (2014)) and the simulation results for the Maca landslide in Peru. (b) Zoom into the behaviour during earthquake shaking showing the input ground motion, cumulative displacements and the evolution of excess pore water pressures in the shear zone. The parameters and geometry are based on the morphology of the landslide (Zerathe et al., 2016). Details on the simulation and the parameters can be found in Kohler & Puzrin (2023).

4.3 Discussion

The presented hydro-mechanically coupled finite element model allows to investigate the potential generation of excess PWP during earthquake loading and the following diffusion process suggested in various studies as the source of post-seismic landslide activity (Bontemps et al., 2020; Lacroix et al., 2022; Marc et al., 2015; Wang & Chia, 2008). The comparison with field observations clearly shows that this model can represent the realistic behaviour of active landslides during and after an earthquake (Kohler & Puzrin, 2023). This not only provides mechanical support for the underlying mechanism, but also allows the identification of the main factors controlling seismic behaviour and represents a tool for a risk assessment. As already seen for the co-seismic behaviour, rate dependence in the shear zone is the key element that explains why slow-moving landslides can withstand such extreme events. Therefore, the calibration using field and laboratory data discussed above also applies to the post-seismic behaviour. This means that landslides with low rate dependency in the shear zone are susceptible to both co- and post-seismic acceleration. The latter also depends on the presence and characteristics of fine-grained layers adjacent to the shear zone. In particular, the permeability and thickness of these layers control the duration of the post-seismic period of increased landslide activity and can be determined using the characteristic time. However, the insitu condition and thus the loading history of these layers is decisive as to whether excess PWP can be generated due to cycling loading at all. In addition, it has been shown that the resulting excess PWP can vary by several orders of magnitude, depending on the characteristics of the earthquake. Therefore, a reliable prediction of post-seismic displacements does not seem realistic and thus the simulations only allow an assessment of possible scenarios.

The landslide model and the gained insight into the underlying physical mechanisms also provide a possibility to investigate the seasonal response of a landslide. Typically, a strong seasonal dependency in the motion of landslides is observed, which is driven by the effect of rainfall and groundwater changes (Alvarado et al., 2019; Bontemps et al., 2020; Handwerger et al., 2019, 2016). The model reaction to a change in the groundwater level could be directly simulated using the proposed model and would even provide an observation-guided calibration of the model parameters (e.g. rate dependency in the shear zone) (Oberender & Puzrin, 2016). Subjecting the model to earthquake shaking in different seasonal states would then allow for a multi-hazard analysis. Given the identified dependency on the pre-seismic velocity, the model predicts a larger post-seismic velocity and displacement for an earthquake during a more active period of the landslide movements. This is due to the logarithmic rate dependent law applied in the shear zone, where for a larger pre-seismic velocity, a larger absolute increase in the landslide velocity is necessary to compensate for the same excess PWP in the shear zone. Moreover, this makes a landslide more susceptible to acceleration due to rainfall events after an earthquake, when its velocity is still elevated. This behaviour has been reported in different studies (Bontemps et al., 2020; Song et al., 2022).

The presented model can also explain the observed phenomena of delayed landslides response, which has been mentioned for the Tapgaon slide in Nepal (Lacroix et al., 2022), but has also been observed for other landslide (Agnesi et al., 2005; Jibson et al., 1994; Keefer, 2002). In case of low permeability, the excess PWP developed in the adjacent layers slowly propagates to the shear zone, leading to a delay and a following phase during which the landslide accelerates to the maximal post-seismic velocity. The reactivation of existing landslides can also be explained by the same mechanism.

5 Assessment of an active landslide

This chapter explains the procedure for assessment of the seismic behaviour of active landslides. The first part focuses on the generation of tsunami waves caused by a catastrophic landslide failure. The aim is to determine whether such a failure is likely. In case this is unlikely, it can still be important to estimate the magnitude of the expected landslide displacement due an earthquake, which will be discussed in the second part.

5.1 Catastrophic collapse

The assessment regarding the generation of tsunami waves comprises 4 stages that will be explained subsequently and is presented in Figure 5.1. If the assessment is made for a landslide that is not located on a lake or reservoir, a wave simulation is not required and only stages 2 and 3 need to be considered.

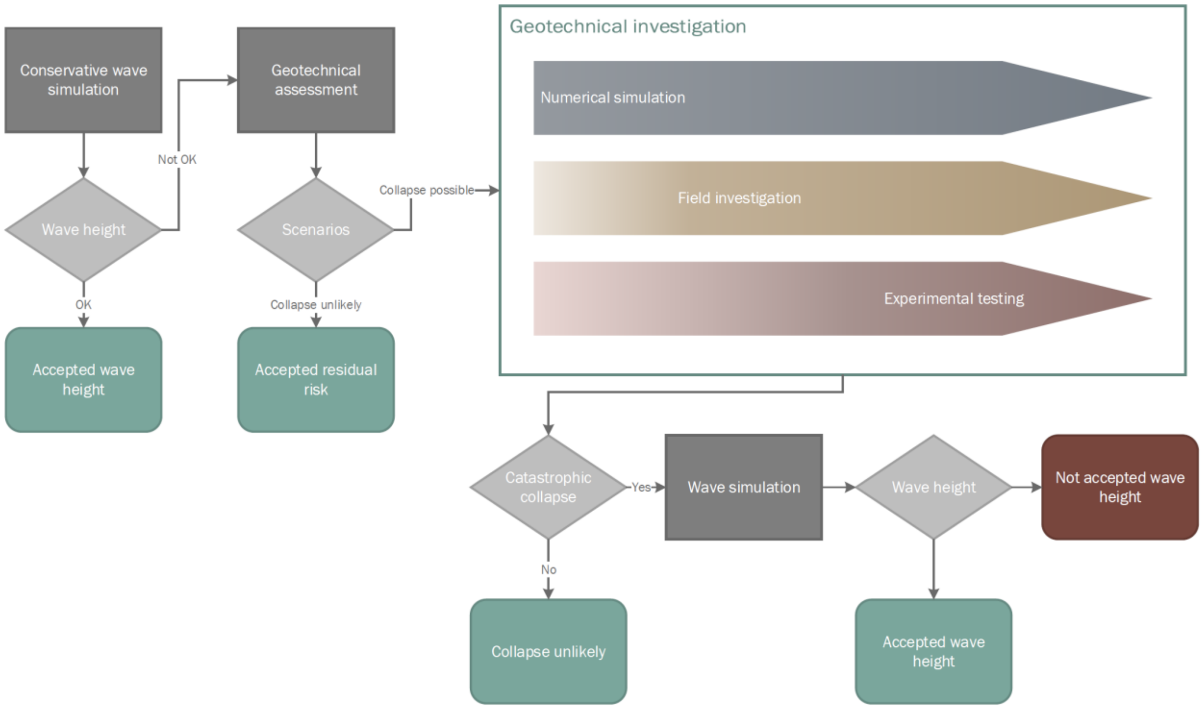

Figure 5.1: General procedure for the assessment of a catastrophic collapse

5.1.1 Stage 1: Conservative wave simulation

The first step of any hazard assessment with respect to an impulse waves caused by catastrophic collapse of a soil mass should be an estimation of the impulse wave assuming (very) conservative properties of the potentially instable slope. If it can be shown that even under such circumstances there is no risk for the dam, further, more complicated assessments may not be necessary.

In this context conservative properties mean that any potential loss of shear resistance either due to development of excess pore pressures or structural softening should be considered as initial condition of the shear zone. This will lead to high velocities of the landslide entering the lake. Additionally, the mass of the landslide should not be underestimated. Using conservative estimates for the landslide mass and velocity will lead to conservative estimates of the impulse wave height and volume. To get estimates of the impulse wave properties refer to e.g. Evers et al. (2023).

5.1.2 Stage 2: Geotechnical assessment

The aim of the geotechnical assessment is to determine whether or not catastrophic failure is likely. This step does not involve any simulations and is based purely on the current state of knowledge of the respective landslide. Potential catastrophic scenarios according to chapter 2 need to be identified and the occurrence of the different failure mechanisms to be evaluated.

First and foremost, it is necessary to know the approximate geometry of the slide. This allows estimating the possible failure volume and assessing whether geometric softening could occur. Equally important is the knowledge of the composition of the landslide mass, if it consists mainly of rock, this also holds a potential for brittle failure and is to be classified as critical. If any of these criteria (or others according to chapter 2) can indicate a catastrophic failure, a more detailed geotechnical investigation is recommended (Stage 3).

In the absence of any indication of catastrophic failure, caution should still be exercised due to the high degree of uncertainty regarding soil behaviour. In order to better assess the risk, the history of the landslide is of particular importance. If it is an old landslide that has been moving for decades or even hundreds of years, it can be assumed that it has already survived extreme events such as heavy rain making a catastrophic collapse less likely. Slow moving landslides can often be the remains of a catastrophic event, which also makes them less susceptible to a sudden failure. However, for landslide at the flank of a water reservoirs, it must not be neglected that their behaviour has been altered and is constantly influenced by the fluctuation of the water level. Therefore, the influence of the reservoir and its relationship to extreme events such as heavy rainfall and earthquakes must be carefully assessed. Particularly useful for this purpose are displacement measurements at different times over several years, which can show the fluctuation of velocities in connection with external influences. The situation can be considered favourable if the long-term trend shows a decrease in landslide velocities. A positive sign are also past heavy rain events, which triggered only a limited and short-term acceleration of the landslide. This indicates a high rate dependency in the shear zone.

The above recommendations are intended as a rough guideline to help assess the risk of a catastrophic collapse. If the geometry, geotechnical structure and history of the landslides are known to some extent, this may already be sufficient. However, this means that a certain amount of residual risk must be accepted. In case of either insufficient knowledge of the landslide or high consequences, it is recommended to perform more detailed geotechnical investigation according to stage 3.

5.1.3 Stage 3: Geotechnical investigation

The geotechnical investigation aims to reduce the uncertainties in the risk assessment in an iterative process. Depending on the reason why stage 2 was not sufficient, the procedure can look different. Figure 5.2 illustrates this process based on the case of the Marsc landslide at the Luzzone reservoir and is described in Kohler (2023). This consist of three parts: Numerical simulation, field investigation and experimental testing. The aim of these is to improve the knowledge of the landslides and in case numerical simulations are carried out to refine these models.

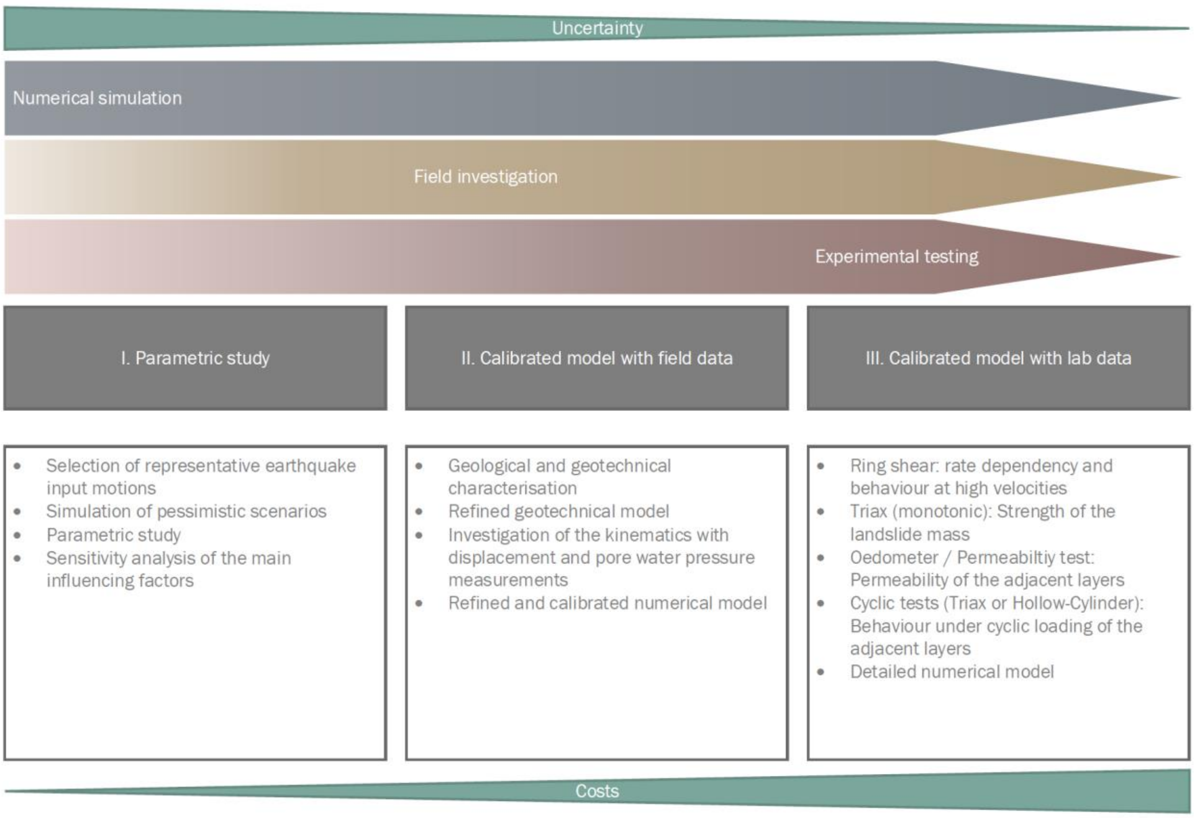

Figure 5.2: Detailed procedure for the geotechnical investigation.

Numerical simulation: The numerical modelling is seen as an important tool to investigate different scenarios. The basis for this is the approximate knowledge of the geometry to create a 2D model. Ideally this is done with the presented seismic MPM framework (see Chapter 3), but also other techniques such as finite element (FE) can be used. However, it is important to uses appropriate seismic boundary conditions and constitutive models. In case of standard FE, the simulations are limited by the amount of deformation and cannot be used to simulate a runout. Nevertheless, it can be used to simulate whether or not a catastrophic collapse can be triggered. The following runout simulation may be performed using a different tool. Following the procedure in Figure 5.2, the first step can be the simulation of pessimistic scenarios and parametric studies in order to determine the range of consequences and to identify the most important factors. Depending on the results, this may already be sufficient and can be accepted with a minor residual risk. Otherwise, this allows a target-oriented field investigation to be planned. It is therefore possible that the numerical simulation has shown that the behaviour of the shear zone needs to be better understood, or that the geometry in an area needs to be refined.

Field investigation: Field investigations are essential for understanding the behaviour of a landslide. Depending on the case and involved mechanisms, their extent can vary greatly. If the landslide has already been well studied, it may be sufficient to carry out a numerical simulation to reduce the residual risk to a minimum. However, if the assessment of the scenarios shows that a mechanism for catastrophic failure is indicated, it can be investigated with targeted field investigation. The main objective are clearly core drillings, as they provide important information about the geological structure of the landslide and can be simultaneously instrumented with displacement and water pressure measurement systems. This improves the knowledge of the geometry and the seasonal behaviour of the landslide. Furthermore, the rate dependency in the shear zone can be evaluated and, if necessary, an appropriate numerical model can be calibrated. Even though laboratory tests are not usually planned at this stage, it is highly recommended that samples be taken from different layers and the shear zone. These can be stored and allow laboratory tests to be carried out later, if necessary.

Experimental testing: Simple laboratory tests such as soil classifications are recommended already at an early stage since they provide important information at rather low costs. In case the strength of the landslide mass is critical for the assessment, monotonic triaxial or direct shear tests can be carried out. For alpine landslides containing large amounts of gravel and cobbles, the sample size needs to be chosen big enough to get representative results. In case the cyclic generation of excess pore water pressure might be critical, it is recommended to determine the permeability in different layers in order to assess whether this excess pressure is likely to propagate into the shear zone. More elaborated tests such as cyclic triaxial and ring shear tests are seen as a last step in the assessment. These tests are not common and require special skills to get meaningful and reliable results. In particular, the standard ring shear tests used for the determination of the residual strength are not suitable to investigate rate dependency at higher velocities. Therefore, a new ring shear apparatus was developed at ETH Zurich (see Chapter 3) for research propose and can be used to determine the rate dependency in critical cases.

5.1.4 Stage 4: Wave simulation

If a catastrophic collapse of the landslide is to be expected, the results of the previous described assessment steps may be used in combination with tools for the assessment of the impulse wave parameters. Potential methods may be:

- Simplified estimation methods like Evers et al. (2023) using aggregated results about mass and entry velocity.
- Numerical methods that allow the simulation of the landslide mass entering the water domain based on the results of the numerical simulation of the previous steps (i.e. landslide collapse simulation and wave generation simulation are decoupled)
- Coupled simulation of the landslide collapse and the generation of the wave generation in one simulation

The results of these assessments will allow for estimating the thread with respect to the dam.

5.2 Co- and post-seismic displacements

In case a catastrophic failure is unlikely, it may still be of interest to predict co- and post-seismic displacements. Especially if housings and structures are in contact with landslides, this can be of great importance to dimension them accordingly or to make a damage assessment. Unfortunately, prediction in only possible to a limited degree because there are that many uncertainties. On the one hand, these relate to the landslide itself, i.e. geometry, geological structure, preconditioning and material behaviour. Even with enormous effort, these things cannot be determined conclusively. This is exacerbated by the uncertainty of the earthquake intensity, location and characteristics.

Nevertheless, this work has shown that a simulation of displacement is achievable and that field observations can be reproduced. For a prediction, this is of course more difficult and is limited to a parametric study, although its uncertainty can be reduced with increasing effort according to Figure 5.3. The procedure is similar to the assessment of a catastrophic failure and is to be understood as an iterative process between numerical simulation, field investigation and experimental testing.

As shown in Chapter 3, the rate dependency in the shear zone is the main factor controlling the co- and post-seismic displacements. Without field and lab data, a parametric study of this rate dependency can be performed to get an idea about the range of possible displacements. Therefore, a set of representative earthquake input motions is required to make a statement for different intensities and characteristics. If the geotechnical classification of the shear zone material has been done, the range of rate dependency can be narrowed down using literature values. However, a considerably more reliable statement can be made if the rate dependency is calibrated using field data. This is therefore essential for the assessment of critical cases. To get more reliable prediction at high velocities, this can be further investigated using appropriate ring shear tests. However, the difficulty with laboratory tests in case of alpine landslides is to get representative results since usually only the finer fraction of samples can be tested. This relativizes the statement about the overall behaviour of the landslide. Moreover, if there is a large variability in the geological conditions, laboratory tests only reflect the local properties. Calibration on field data, on the other hand, is a homogenised approach that describes the behaviour in an averaged manner. However, extrapolation to higher than seasonally measured landslide velocities is a source of uncertainty.

Furthermore, there is an additional uncertainty due to the entire landslide mass. This is less important for weak earthquakes, as the movement is mainly localized in the shear zone. During strong motions, depending on the geometry, the landslide mass is more deformed, which increases the influence of its behaviour on the resulting displacements.

Another problem is the cyclic generation of excess pore water pressures. These can co-seismically reduce the resistance of the sliding mass and thus lead to increased displacements and, as explained in Chapter 4, to an increased post-seismic activity. Modelling the cyclic behaviour of soils, even when cyclic tests have been carried out, is still a complex task and requires sophisticated constitutive models. On top of that, there is still a considerably uncertainty, as the insitu conditions (i.e. porosity and the loading history) can only be determined to a limited extent.

Finally, the presented models for co- and post-seismic simulations are not standard methods and are usually not available.

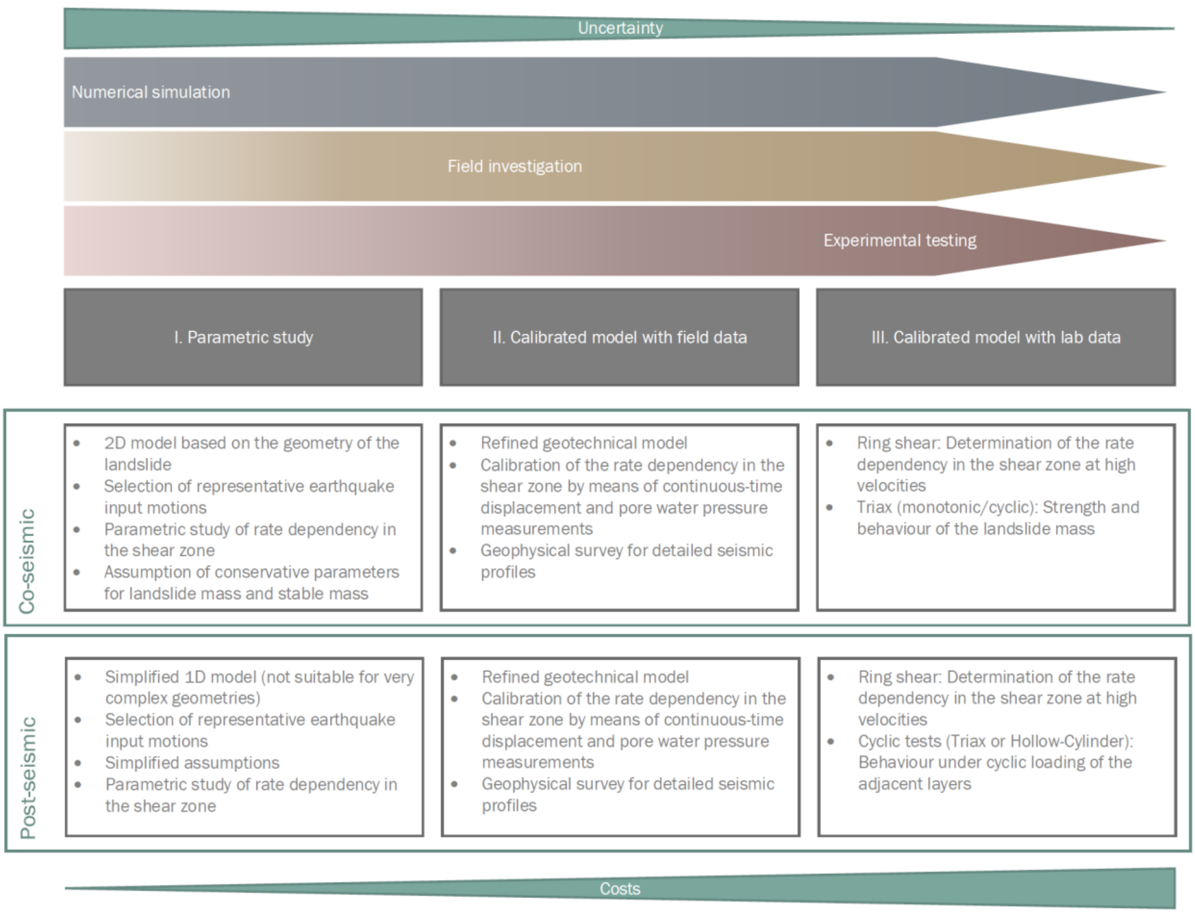

Figure 5.3: Procedure for the assessment of co- and post-seismic displacements

Please note that simplified assessment methods such as Newmark's sliding block method should be used with great caution, as they are very sensitive to the assumptions made with respect to the governing parameters. Figures 5.5 and 5.6 show for the Campo and Brienz landslides in Switzerland the results of a Newmark's sliding block analysis compared to the MPM simulation. As can be seen, since Newmark's model only depends on the estimate for rate dependency and cannot account for the effect of geometry of the landslide. Consequently, the results are very sensitive to the assumption of rate dependency. Therefore, great caution is recommended when using strongly simplified models and it should always be assessed if such a method may be an acceptable simplification of the landslide or oversimplifies the situation.

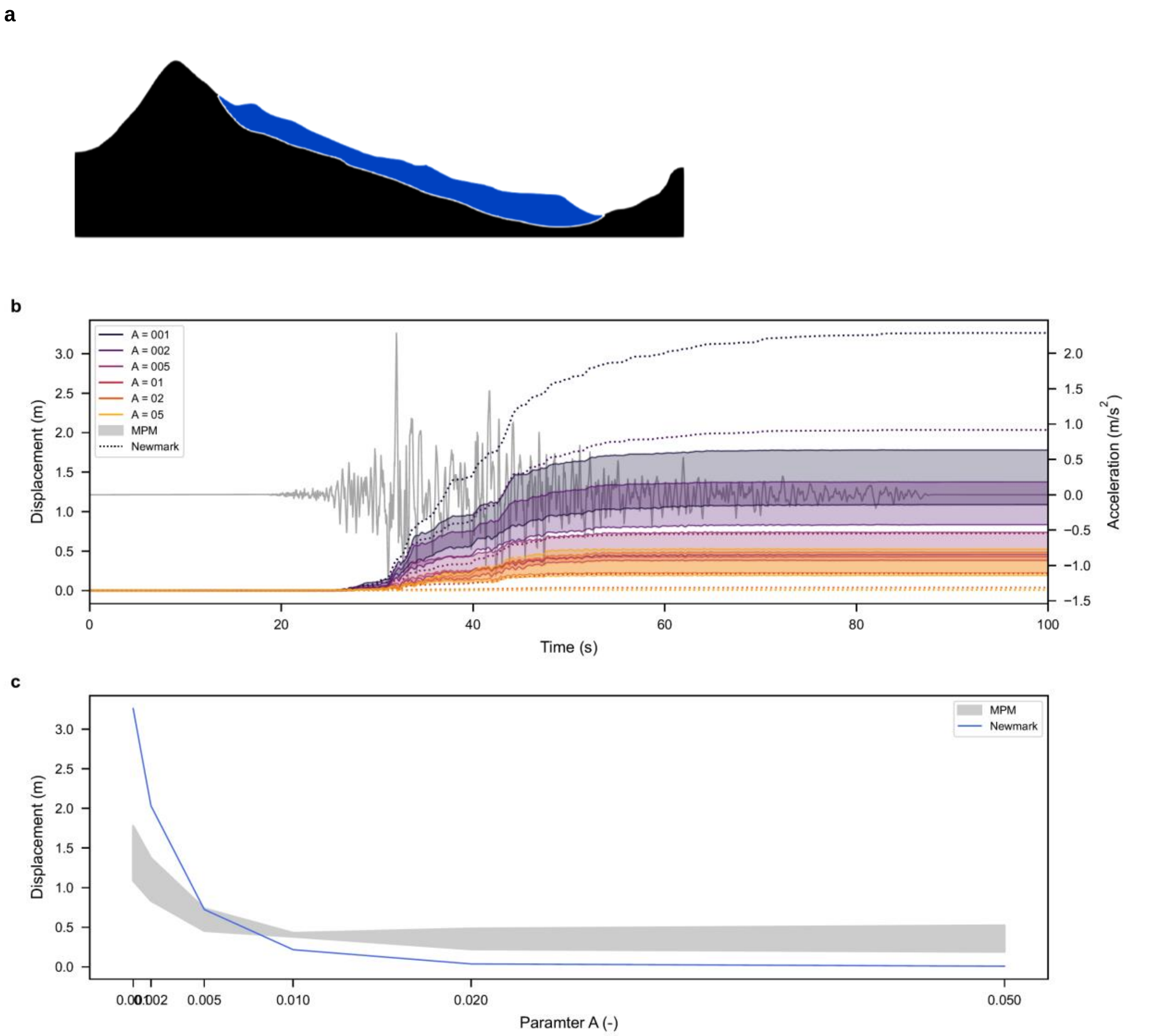

Figure 5.5: Co-seismic displacement for the Campo landslide in Switzerland. (a) Geometry of the Campo landslide. (b) and (c) comparison of the MPM simulation with a simplified Newmark for different rate dependency parameters A. The MPM simulation provides co-seismic displacements at each point of the landslide. The range of displacement is therefore represented as a hatch.

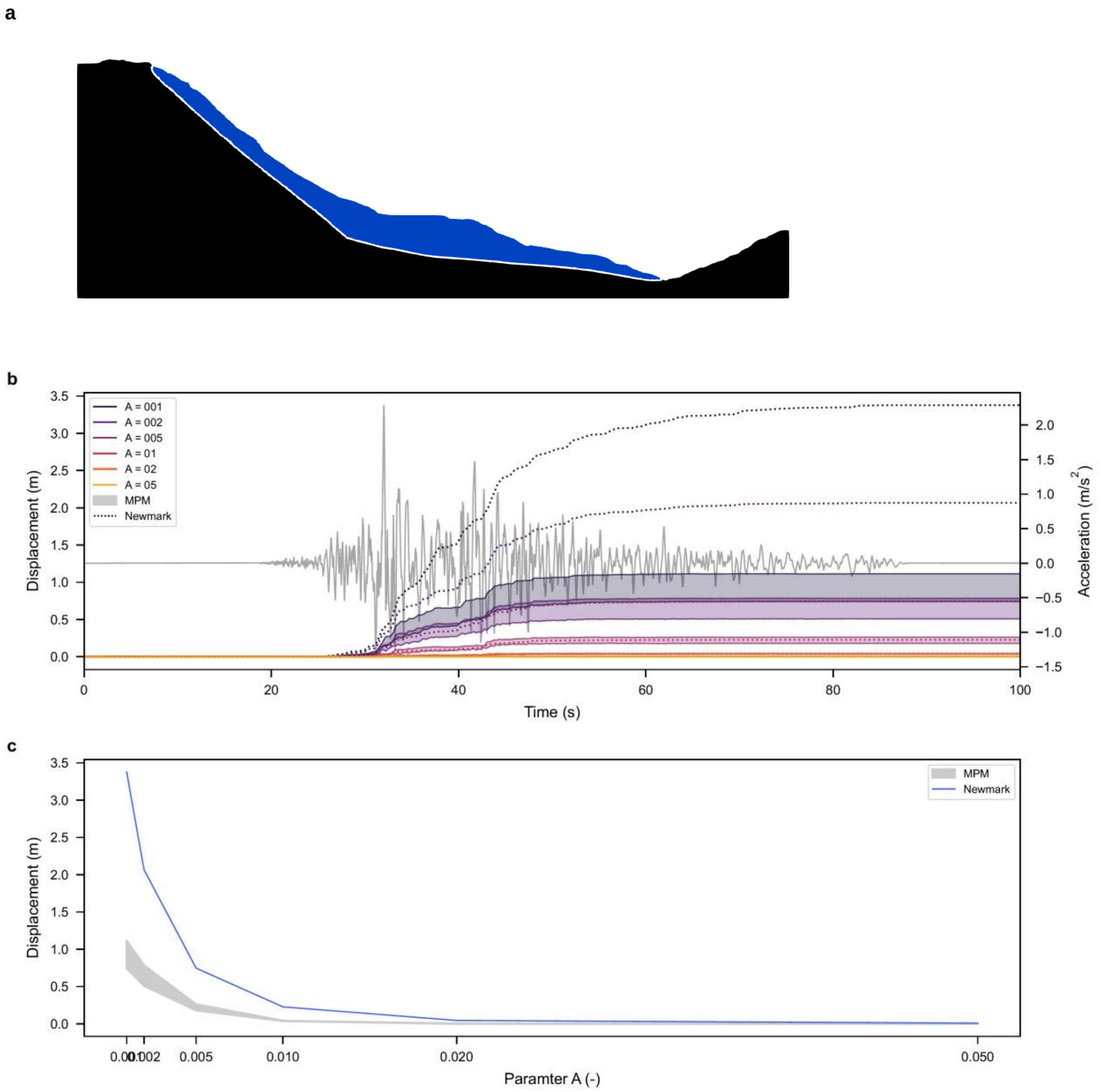

Figure 5.6: Co-seismic displacement for the Brienz landslide in Switzerland. (a) Geometry of the Brienz landslide. (b) and (c) comparison of the MPM simulation with a simplified Newmark for different rate dependency parameters A. The MPM simulation provides co-seismic displacements at each point of the landslide. The range of displacement is therefore represented as a hatch.

5.2.1 Modelling post-seismic displacements

Due to the potential development of excess pore pressures, landslides may also displace after an earthquake is over, i.e. exhibit post-seismic displacements. These can be significant and may even exceed co-seismic displacements. Therefore, if the magnitude of potential displacements are of interest post-seismic behavior needs to be assessed. Two general options are possible as shown in figure 5.7:

- Decoupled analysis: The excess pore pressures generated during an earthquake are calculated independently from the assessment of the co-seismic displacements; subsequently the dissipation of the excess pore pressure is estimated in another model and the resulting pore pressure evolution over time is applied directly to the slip surface of the landslide model allowing to estimate the induced displacements. There are a multitude of methods based e.g. on shear strain, equivalent cycles, dissipated energy etc. to estimate the buildup of excess pore pressures during an earthquake. Unfortunately, the choice and calibration of such models is not a trivial task and experts should be involved for this step.
- Coupled analysis: In case the tool which is used for numerical simulation of the landslide allows to include the built up of pore pressures within constitutive models of the landslide materials both co-seismic displacement and pore pressure built up can be simulated simultaneously and subsequently the post-seismic stage can be assessed.

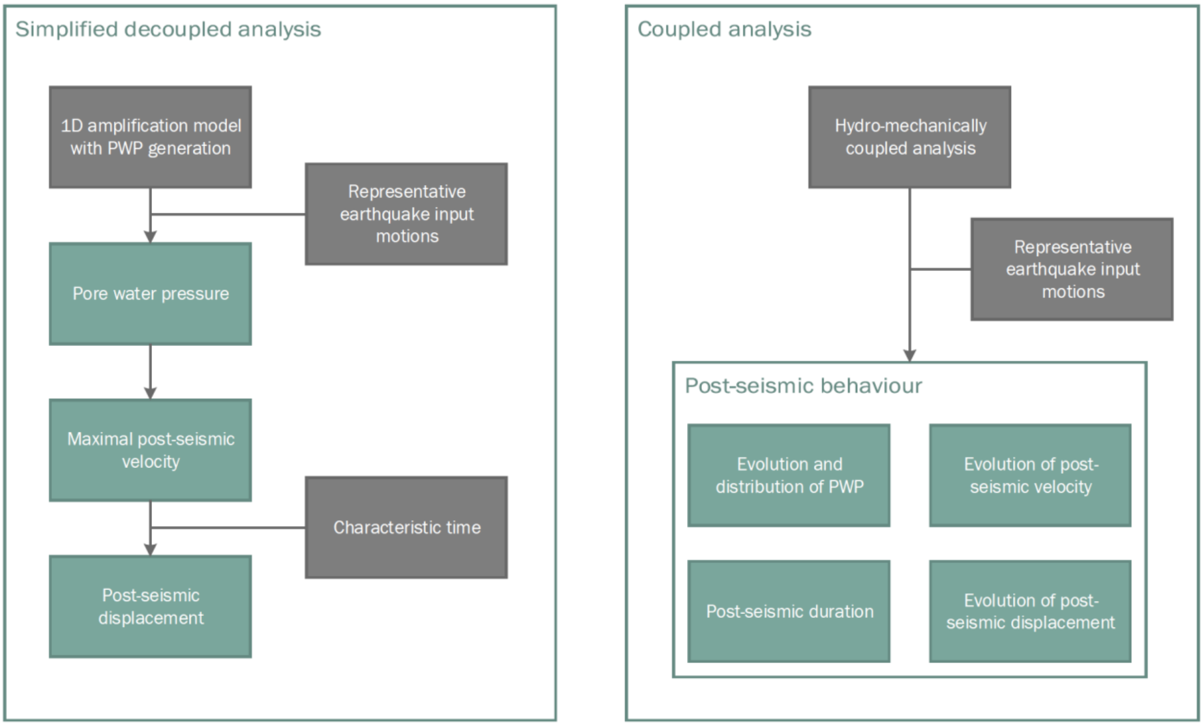

Figure 5.7: Procedure for the assessment of post-seismic displacements

6 Summary and Conclusions

Assessing the threat posed by active landslides at reservoir flanks remains a very challenging task. Within this project novel modelling techniques and improved experimental testing devices have been combined with extensive field investigations. However, the effort necessary to perform a comprehensive assessment of the landslide including all mentioned aspects may be very large. Therefore, a stepwise process is recommended that starts with a landslide model and conservative material assumptions and removes conservativism with increasing investigative effort.

With respect to **numerical modelling**, it must be clearly stated that strongly simplified models such as Newmark's sliding block are very sensitive to material properties that are difficult to derive. Therefore, modelling techniques that account for the landslide geometry are clearly preferable and will allow for initial assessment of whether the landslide can pose a threat.

With respect to **field investigations,** an extensive investigation for the Marsc landslide at the Luzzone water reservoir has been presented. This project provides an in-depth understanding of the kinematics of the landslide and reveals the interactions between the groundwater level in the landslide, the reservoir level and the observed velocities. This has been the basis for the formulation and calibration of the geotechnical landslide model. It is recommended to use results from initial modelling of the landslide to identify the most important aspects, e.g., how extensively should the geometry of the slip surface be investigated. Please note, that in case laboratory investigations are planned it is necessary to derive samples from the slip surface zone. If the depth of the slip surface is initially unknown, it may be difficult to identify the correct sample. This must either be determined based on the geology or, better (since the former is usually inconclusive), all samples must be stored temporarily and the depth of the shear zone and thus the corresponding sample must be identified by means of an inclinometer measurement.

With respect to **laboratory investigations,** a new ring shear apparatus has been developed and manufactured at ETH Zurich. This ring shear device allows measuring the extremely small rate dependency effects that control the movement of the landslide. However, such tests remain challenging and should be performed by experts. The same is true for tests (e.g. cyclic triaxial test) that assess the build-up of pore pressures.

Overall, results of this work indicate that active landslides can be less susceptible to co-seismic acceleration than previously thought. There are two main reasons for this - the rate dependency of the shear strength and the geometry of the landslide. Both effects are neglected by the conventional Newmark's sliding block analysis, making its application unsuitable for active landslides. In contrast, the MPM technique presented here is a powerful tool that incorporates these and other factors that may be required for the analysis of other types of active landslides.

These findings do not imply that the seismic behaviour of active landslides is irrelevant. On the one hand, potential scenarios need to be carefully assessed if major consequences are to be expected, e.g.

in the case of water reservoirs. On the other hand, if infrastructure and buildings are built on or are in contact with the landslide, estimation of co- and post-seismic displacements can become critical. Most importantly, it is recommended that not only already moving slopes at reservoir flanks are being assessed but attention should also be given to slopes that seem stable as those might still experience softening that may lead to catastrophic collapse of the slope.

7 Publications

Kohler, M. (2023). Effects of Earthquakes on the Mechanics of Active Landslides. Doctoral Thesis. ETH Zurich.

Kohler, M., Hodel, D., Keller, L., Molinari, A. & Puzrin, A. M. (2023). Case Study of an Active Landslide at the Flank of a Water Reservoir and its Response During Earthquakes. Engineering Geology. https://doi.org/10.1016/j.enggeo.2023.107243

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