UNIVERSITAT POLITÈCNICA
DE CATALUNYA
BARCELONATECH

MPM modelling of landslides in brittle and unsaturated soils

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A thesis submitted to the Universitat Politècnica de Catalunya (UPC)
in partial fulfillment of the requirements for the degree of
DOCTOR OF PHILOSOPHY

Ph.D. program on Geotechnical Engineering and Geo-Sciences
Department of Geotechnical Engineering and Geo-Sciences
Barcelona, September 2015

Thesis written by Alba Yerro Colom

This work has been supported by FPI/UPC Research Fellowship Program, ref. BES-2009-018300 under the project BIA2008-06614

Cover Picture: Cecil Lake road landslide, Peace River. Photo by R. Couture, Geological Survey of Canada.

A la meva família,

Acknowledgments

En primer lugar, me gustaría expresar mi sincero agradecimiento a mi tutor, Eduardo Alonso, por apoyarme y orientarme a lo largo de estos años. De él he aprendido muchísimo y sigo aprendiendo cada día, de su rigor científico y de sus explicaciones que hacen fácil lo difícil.

També vull donar les gràcies a la meva co-tutora, la Núria Pinyol, per donar-me la seva visió crítica la qual sempre m'ha motivat per seguir millorant.

I want to extend my gratitude to Professor Pieter Vermeer for his guidance during my stage in Deltares (Delft, The Netherlands) and for giving me the opportunity to be a member of the MPM group.

Vull agrair al professor Jordi Corominas que em descobrís el món de la recerca durant la realització de la meva tesina de final de carrera. Probablement, sense aquesta bona experiència, no hagués iniciat un doctorat.

També vull donar les gràcies als professors del departament que desinteressadament han dedicat part del seu temps als meus dubtes: l'Ignasi Carol, l'Antonio Lloret, el Josep Suriol, l'Antonio Gens, l'Alberto Ledesma i el Marcel Hürlimann. En especial al Sebastià Olivella, pels seus consells, per escoltar-me i ajudar-me des del principi. También a Jean Vaunat, por sus ánimos y por estar siempre predispuesto a ayudar.

Agraeixo al personal de secretaria del Departament d'Enginyeria del Terreny: l'Eva Martínez, l'Óscar Rubio, la M. Carmen Rodríguez i la Mar Obrador, per facilitar els tràmits administratius. També a l'Albert Marquès, pel seu suport informàtic.

Aquesta tesis s'ha pogut realitzar, principalment, gràcies al suport econòmic del Ministerio de Ciencia e Innovación i la Universitat Politècnica de Catalunya a través de la beca FPI BES-2009-018300. Durant els dos primers anys, el Col·legi d'Enginyers de Camins Canals i Pots també hi ha contribuït econòmicament.

I would like to express my gratitude to my colleges from Deltares and the MPM Research Community: Lars Beuth, Shuhong Tan, Alex Rohe, Mario Martinelli, James Fern, Francesca Ceccato, Issam Jassim, Phuong Nguyen, and Fursam Hamad, for their collaboration and friendly support.

M'agradaria agrair als meus companys de doctorat, de despatx i de congressos: el Guillem Domènech, l'Olga Mavrouli, el Mauricio Tapias, l'Ivan Puig, la Natàlia Climent, el Mauricio Albarado, el Víctor Serri, la M. Teresa Yubero, el Crístian De Santos, el Dani Garolera, el Joaquín Liaudad, l'Héctor Marín, el Jubert Pineda, la Joanna Butlanska, la Claudia González i l'Héctor Levatti, per tots els bons moments compartits i per ajudar-me sempre que ho he necessitat. Especialment a la Clàudia Abancó i a l'Anna Ramon, per la confiança i els seus consells sobre la tesis i la vida.

També vull recordar als dos estudiants que han realitzat les seves tesines dins el marc d'aquest treball, l'Helena Castellví i el Francesc Mirada.

Gràcies també al grup de "telecos": el Dani Monells, el Rubén Iglesias, el Giuseppe Centolanza, l'Edu Makhoul, el Marc Imbert i l'Alberto Alonso, per la vostra amistat i les converses animades que m'han dibuixat un somriure cada matí.

I would also like to thank my iranian housemates of *kikkerweg*, Sepehr Eslami and Nima Sharif, you did my stay in The Netherlands unbelievable.

Vull estendre el meu agraïment a l'Arnau Clot pel seu suport i les incomptables discussions enriquidores. I, molt sincerament, al Pau Pujadas per ajudar-me tant i motivar-me quan més ho he necessitat.

Deixo pel final als més importants, la meva família i a la meva parella. Els hi vull donar les gràcies per estar al meu costat i per encoratjar-me en els moments més difícils. Per la seva comprensió, per ensenyar-me a gaudir de les petites coses i a viure intensament. Sense vosaltres hagués sigut impossible.

Abstract

Landslides and slope instabilities represent one of the most important problems in geotechnics causing significant damages around the world every year. Understanding the mechanics of the whole deformation process is of particular importance for risk assessment. First, it is important to determine what areas may be susceptible to landsliding. In addition, it is essential to estimate the travelled distance and the velocity of the unstable mass in order to prevent severe damage. The need to develop solution schemes capable of simulating failure initiation as well as post-failure dynamics is also required in most geotechnical analyses. For instance the design of dams, tunnels, pipes or foundations.

The numerical modelling of such events presents several challenges due to the complexity of simulating large deformations and real soil behaviour. In addition, coupled formulations are needed to model solid-fluid interaction in saturated and unsaturated soils.

Traditional geotechnical analysis, such as Limit Equilibrium Methods (LEM) and the well-known standard lagrangian Finite Element Methods (FEM) are very useful to study the failure initiation, but they provide limited information on the post-failure behaviour. In order to overcome such difficulties, modern numerical approaches are being developed. This is the case of the Material Point Method (MPM), which offers an interesting alternative. MPM discretises the media into a set of lagrangian material points which move attached to the material carrying the soil properties. Governing equations are solved incrementally at the nodes of a computational grid that remains fixed through the calculation. This dual description of the media is capable of modelling large deformations and prevents mesh tangling.

This thesis focusses on studying brittle failures and slope instabilities, from static conditions to run-out by means of the MPM framework. It is proved to be a very useful tool to analyse relevant aspects for the interpretation of landslides such as the development of progressive failure mechanism, the role played by internal shearing in compound slides, and the effect of brittleness on the onset of failure and run-out. The MPM is successfully applied to solve several slope instability problems caused by pore pressure changes. First, the Selborne slope experiment is simulated. This case, well identified with laboratory data, has been an opportunity to perform a validation of the MPM formulation, since a good agreement is obtained between numerical results and experimental data. In a second example, a simplified geometry of the Vajont landslide is analysed. It has shown that a kinematically admissible failure mechanism requires internal degradation of the mobilised

mass controlled by the geometry of the basal sliding surface. In a third analysis, a parametric study varying peak and residual strength is presented, and run-out is found to be directly related with brittleness index.

Moreover, a step forward in the application of MPM to solve multi-phase problems in porous media has been achieved. A coupled 3-phase 1-point MPM formulation is derived and implemented in a software code in order to model problems involving large deformations in unsaturated soils. In this way, the interaction of three different phases (solid, liquid and gas) is taken into account within each material point. This approach is validated with a benchmark problem and it is applied to study the behaviour of an embankment slope instability induced by heavy rain.

Finally, two constitutive models are derived and implemented: a brittle model with strain softening for saturated soils, and a Mohr-Coulomb elastoplastic model for unsaturated materials formulated in terms of net stress and suction.

Resum

Les esllavissades representen un dels problemes més destacats en el camp de la geotècnia ja que cada any causen danys importants arreu. L'estudi d'aquests procesos és fonamental per l'avaluació de riscos. En primer lloc, és important determinar les zones susceptibles a lliscaments o inestabilitats, i per altra banda, és essencial estimar la velocitat i la distància recorreguda per la massa desestabilitzada. El desenvolupament de tècniques numèriques amb la capacitat de simular de forma unificada des de l'inici de la trencada fins a l'estabilització final són claus en problemes d'estabilitat de talussos, així com també en altres anàlisis geotècnics, com per exemple, en estudis d'estabilitat de preses, túnels, canalitzacions o fonamentacions.

La predicció d'aquest tipus d'episodis catastròfics presenta diversos reptes a causa de la dificultat de modelar problemes que impliquen grans deformacions del terreny. A més, el comportament real del sòl és complex i, en molts casos, es requereix la implementació de formulacions hidro-mecàniques per tal de tenir en compte l'efecte de fluids (líquid i/o gas) en terrenys saturats i parcialment saturats.

Les tècniques més tradicionals, com ara els Mètodes d'Equilibri Límit (LEM) i la formulació clàssica del Mètode dels Elements Finits (FEM), són molt útils per estudiar l'inici de la trencada, però proporcionen informació molt limitada del comportament de la massa involucrada un cop ha trencat.

Actualment, s'estan desenvolupant eines numèriques per tal de de simular tot el procés (trencament i post-trencada), com per exemple el Mètode del Punt Material (MPM) el qual ofereix una alternativa interessant. El MPM discretitza el medi continu mitjançant un conjunt de punts lagrangians (punts materials) que es mouen units al material i transporten les seves propietats. Per altra banda, les equacions de govern es resolen de forma incremental als nodes d'una malla computacional que roman fix durant tot el càlcul. Aquesta doble discretització permet la simulació de grans deformacions i evita problemes de distorsió de malla, típics en el FEM.

Aquesta Tesi es centra en la simulació d'inestabilitats de talussos mitjançant el MPM. Es demostra que el MPM és una eina molt potent per analizar tant les condicions estàtiques inicials, com la formació del mecanisme de trencament i el comportament post-trencada. A més, es descriuen diferents aspectes rellevants per a la interpretació de les esllavissades: el desenvolupament del mecanisme de trencada progressiva, l'efecte de la fragilitat i la

degradació interna del material. El MPM s'ha aplicat amb èxit en diferents problemes d'estabilitat de talussos causats per canvis de la pressió intersticial. En primer lloc, es presenta l'experiment de Selborne. Aquest exemple ha servit per validar la formulació del MPM ja que s'ha aconseguit un bon ajust entre resultats numèrics i dades experimentals. En un segon model, s'analitza una geometria simplificada de l'esllavissada de Vajont, amb la qual es demostra que un mecanisme de trencada cinemàticament admissible requereix de la degradació interna de la massa mobilitzada depenent de la geometria de la superfície basal de lliscament. En tercer lloc, per mitjà d'un estudi paramètric variant les resistències pic i residual, s'ha determinat que l'abast està directament relacionat amb la fragilitat del terreny.

Un objectiu important de la tesis ha estat donar un pas endavant en l'aplicació del MPM per tal de resoldre problemes multi-fàsics en medis porosos. Es presenta un esquema hidro-mecànic acoplat per simular el comportament de sòls no saturats que té en compte la interacció de sòlid, líquid i gas en cada punt material. Aquest formulació s'ha validat mitjançant un problema d'infiltració, i s'ha aplicat per estudiar la inestabilitat d'un terraplè induïda per fortes pluges.

Finalment, s'han presentat i implementat dos models constitutius: un model amb reblaniment per sòls saturats, i un model elastoplàstic Mohr-Coulomb per a sòls no saturats formulat en termes de tensió neta i succió.

Resumen

Los deslizamientos constituyen una de las amenazas naturales más relevantes en el campo de la geotecnia ya que cada año causan daños importantes en todo el planeta. El conocimiento de la mecánica del proceso de inestabilidad del deslizamiento es fundamental en la evaluación de riesgos. En primer lugar, es importante determinar las zonas que pueden ser susceptibles a estos fenómenos. Además, es esencial estimar la velocidad y la distancia recorrida por la masa inestable. El desarrollo de técnicas numéricas capaces de simular de forma unificada desde el inicio de la rotura hasta el equilibrio final son claves en problemas de estabilidad de taludes así como también en otros análisis geotécnicos, tales como estudios de estabilidad de presas, túneles, canalizaciones o cimentaciones.

La predicción de este tipo de episodios catastróficos presenta varios retos debido a la dificultad de modelar grandes deformaciones. Además, el comportamiento real del suelo es complejo y la implementación de formulaciones hidro-mecánicas es determinante para tener en cuenta el efecto de fluidos (líquido y/o gas) en terrenos saturados y parcialmente saturados.

Los análisis geotécnicos tradicionales, tales como los Métodos de Equilibrio Límite (LEM) y la formulación clásica del Método de los Elementos Finitos (FEM) son muy útiles para estudiar el inicio de la rotura. Sin embargo, estos métodos proporcionan información muy limitada de la post-rotura y del comportamiento de la masa movilizada.

Actualmente, se están desarrollando herramientas numéricas capaces de simular de forma unificada todo el proceso (rotura y post-rotura), como por ejemplo el Método del Punto Material (MPM) que ofrece una alternativa interesante. El MPM discretiza el medio continuo mediante un conjunto de puntos lagrangianos (puntos materiales) que se mueven unidos al material y transportan sus propiedades. Por otra parte, las ecuaciones de gobierno se resuelven de forma incremental en los nodos de una malla computacional que permanece fija durante todo el cálculo. Esta doble discretización permite simular grandes deformaciones y evita los problemas de distorsión de malla típicos en el FEM.

Esta Tesis se centra en la simulación de inestabilidades de taludes mediante el MPM. Se ha demostrado que el MPM es una herramienta muy útil para analizar tanto las condiciones estáticas iniciales, como la formación del mecanismo de rotura y el comportamiento post-rotura. Además, se describen diferentes aspectos relevantes para la interpretación de los deslizamientos: el mecanismo de rotura progresiva, el efecto de la fragilidad y la

degradación interna del material. El MPM se ha aplicado con éxito para resolver diversos problemas de inestabilidad de taludes causados por cambios de presión intersticial. En primer lugar, se simula el experimento de Selborne. Este ejemplo ha servido para llevar a cabo la validación de la formulación MPM ya que se ha conseguido un buen ajuste entre resultados numéricos y los datos experimentales. En un segundo modelo, se considera una geometría simplificada del deslizamiento de Vajont en el que se analiza la degradación interna de la roca movilizada debido a esfuerzos cortantes. En tercer lugar, por medio de un estudio paramétrico variando las resistencias pico y residual, se determina la relación entre el alcance del deslizamiento y la fragilidad del material.

Uno de los objetivos de la Tesis ha sido dar un paso adelante en la aplicación del MPM para resolver problemas multi-fásicos en medios porosos. Se presenta un esquema hidromecánico acoplado para simular el comportamiento de suelos no saturados que tiene en cuenta la interacción de sólido, líquido y gas en cada punto material. Esta formulación se ha validado mediante un problema de infiltración, y se ha aplicado para estudiar la inestabilidad de un terraplén causada por fuertes lluvias.

Finalmente, se han presentado e implementado dos modelos constitutivos: un modelo con reblandecimiento para suelos saturados, y un modelo elastoplástico Mohr-Coulomb para suelos no saturados formulado en términos de tensión neta y succión.

Contents

1

Chapter 1
Introduction

In this first Chapter, the motivation of this work is presented in order to justify its raison d'être. Then, the main goal as well as several specific objectives are stated. Finally, the organisation of the document is also outlined.

1.1 Motivation

Landsliding represents one of the most important problems in geotechnics causing significant damages around the world every year (see Figures 1.1 and 1.2). Understanding the mechanics of the whole process is of particular importance for risk assessment. First, it is important to determine what areas may be susceptible to landsliding. Second, it is essential to estimate the travelled distance and the velocity of the unstable mass in order to prevent severe damage. For instance, when reservoirs, lakes or fjords are potentially affected by landslides on their margins, the calculation of tsunami effects require information on the soil/rock mass run-out and its expected velocity.

The need to develop solution schemes capable of simulating failure initiation as well as post-failure dynamics is also required in most geotechnical analyses. For instance the design of dams, tunnels, pipes, foundations or embankments. Ensuring the stability of these constructions is the most important issue. Despite the probability of failure at the initiation stage is often small, soil and rock as natural geological materials exhibit spatial variability and the uncertainty is always existent. Therefore, in these cases, it is

Figure 1.1: La Conchita landslide, coastal area of southern California. Occurred in the spring of 1995. People were evacuated and the houses nearest the slide were completely destroyed. Photo by R.L. Schuster, U.S. Geological Survey.

Figure 1.2: Cecil Lake road landslide, Peace River. Photo by R. Couture, Geological Survey of Canada.

also important to understand the post-failure behaviour so that the risk of catastrophic damage can be minimised.

The prediction of such catastrophic episodes presents several challenges due to the complexities of real soil behaviour. In addition, since many geotechnical problems often involve seepage forces, the consideration of the coupled behaviour of soil and pore fluids is essential by means coupled hydromechanical formulations.

Rain-induced instabilities are very common especially in partially saturated soils. Natural or cut slopes may remain stable for long times under unsaturated conditions due to the positive effect of the suction on the strenght, and then they fail during heavy rainstorms or after a long period of rain. Often, they are shallow failures that involve large deformations of the mobilised mass. Other applications associated with unsaturated soils involve large deformations in history-dependent constitutive models. This is the case of swelling problems in expansive clays or collapse behaviour of low density materials.

There is much to learn about the evolution of failure in landslide systems, and in particular about the ways in which fracture initiation allows the development of the final failure surface. When examined in detail, one of the factors causing the acceleration of landslides is the loss of strength of the soil involved in a potential unstable mechanism. This typically occurs in brittle materials such as overconsolidated plastic clays and cemented soils, which are characterised with a strain softening behaviour. In these cases, a progressive failure mechanism is developed. During the failure process, slope deformations tend to be small because of the stiff nature of brittle clays. However, the subsequent motion, controlled by Newton law, can involve rapid movements. The consequences of the instability depend on many aspects, typically related to the strength of the failure surface and to the geometry of the site at a larger scale.

Except for simple sliding motions, the stability of a slope not only depends on the resistance of the basal failure surface. For instance, it is also affected by the distortion of the moving mass in compound slides. Internal shearing plays an important role on the stability and post-failure behaviour of a landslide (Fell et al., 2007; Glastonbury and Fell, 2010).

Traditional geotechnical analysis, such as Limit Equilibrium Methods (LEM), are very useful to estimate the failure initiation, but these simple solutions can not provide information on movements and are unable of simulating real soil (or rock) behaviour. The well-known lagrangian Finite Element Methods (FEM) can model complex geometries and they are well suited to integrate advanced constitutive models. However FEM provides limited information on the post-failure behaviour due to mesh tangling problems when large displacements are involved.

Modern numerical algorithms are being developed in order to provide an integrated tool capable of simulating the entire instability process in a unified calculation: the static stability associated to small deformations, the failure triggering and the large displacements during the subsequent run-out. This is the case of the Material Point Method (MPM).

MPM has been applied to a number of geotechnical problems and it has been extended to solve coupled flow-deformation problems in saturated conditions. It is considered as a Particle-based method with some features from Finite Element analysis. It uses two different spatial discretisation schemes to describe the continuum: a set of lagrangian material points that move with the material and carry all the information, and a fixed computational mesh in which the governing equations are solved. The dynamic formulation and the dual description of the media provide the MPM the capabilities of handling problems involving large displacements and deformations.

1.2 Objectives

This Thesis focuses on developing the Material Point Method with the aim of modelling geotechnical problems involving large deformations, such as the whole instability process of a landslide, in brittle and unsaturated soils. In order to achieve such general purpose, the following specific objectives are formulated.

Regarding numerical improvements:

- To extend MPM to analyse problems in unsaturated soils by means a 3-phase (solid, liquid and gas) dynamic coupled hydromechanic formulation

- To implement elastoplastic constitutive models capable of simulating brittle soil behaviour and effects in strength due to suction changes

- To study the numerical stability of explicit schemes and to propose a criterion to calculate critical time step increments

Regarding geotechnical knowledge:

- To test the capability of MPM to model large deformations by simulating a real slope instability case, from initiation and failure propagation to final geometry and run-outs.

- To understand the development of progressive failure mechanisms in brittle materials

- To determine the influence of brittleness in landslide run-out and kinematics of the motion

- To examine the effect of internal shearing in the stability conditions and the post-failure behaviour of compound landslides

- To model unsaturated soil behaviour under rainfall conditions

1.3 Thesis layout

The Thesis is organised in 8 chapters. The main contents are introduced here:

In Chapter 2, a general review of the most important numerical methods used in geotechnics is presented. These are divided in Mesh-based and Particle-based methods. MPM is briefly described, and the main reasons why it has been preferred against others are outlined.

Chapter 3 begins with a literature review regarding the origins and applications of MPM. Then, the basis of the method are presented in a general framework of mechanical problems. The 1-phase MPM formulation and its explicit numerical implementation are detailed. The dynamic formulation is validated through the analysis of a wave propagation problem and a blasting example is presented.

In Chapter 4, the 2-phase 1-point MPM formulation is describedfor fully saturated soil and several numerical issues are discussed. A stability analysis of the integration scheme is carried out and a practical criterion to determine the critical time step size is proposed. The damping of the solution and boundary conditions are also outlined. This approach is validated by means of the one-dimensional consolidation problem.

Chapter 5 focuses on modelling landslide initiation and post-failure evolution in brittle materials. The progressive failure phenomenon is described and the non-associated Mohr-Coulomb is extended by introducing strain softening plasticity. Afterwards, three slope instabilities triggered by the increase of pore water pressure are analysed. First, the Selborne failure experiment is modelled. Then, the effect of internal shearing in a compound slide based on Vajont landslide is discussed. Remarkable consistent and accurate results are achieved. Additionally, the influence of the brittleness is evaluated on the triggering of instability and run-out for a typical slope geometry by means a parametric study.

In Chapter 6, the MPM formulation is extended to model problems involving unsaturated soil. From a computational point of view, the soil is understood as a unique medium integrated by three distinct phases (solid, liquid and gas). After a short discussion of which are the possible MPM strategies capable of simulating such solid-fluid interaction problems, a 3-phase 1-point MPM formulation is presented. The implementation of this approach is validated with a benchmark problem against an analytical solution.

In Chapter 7 the instability of an unsaturated slope subjected to rain infiltration is solved and discussed. A suction-dependent elastoplastic Mohr-Coulomb model is presented in order to simulate strength changes due to wetting effects. The development of the initial failure surface, the evolution of stress and suction states, and the dynamics of the motion are presented.

Finally, in Chapter 8, the general conclusions are summarised and future works are outlined.

To give a complete understanding of this work, additional Appendices are included.