UNDERGRAD. THESIS

NUMERICAL STUDY OF LARGE STRAIN DEFORMATION IN LOAD INDUCED SLOPE FAILURE USING MATERIAL POINT METHOD

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PERNYATAAN

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ABSTRACT

The case of large deformations presents a challenging problem to be simulated numerically. In recent years, the development of meshfree methods especially the Material Point Method (MPM) has gained some tractions and shown some significant progresses. This thesis aims to utilize this method for analyzing a large deformation case found in load induced slope failure. Thus, a hypothetical slope geometry is chosen to be modeled and analyze in regard to varying soil strength parameter and incremental uniform load. Next, the results are divided into two criteria, small strain deformation and large strain deformation. Then, a comparison study is performed between MPM and Finite Element Method (FEM) in the small strain deformation region in order to investigate MPM. The outcome shows that MPM produce relatively consistent results compared to FEM results in all the case variants. In the large deformation region, MPM also presents failure geometries along with the corresponding mechanical properties throughout the failure process. However, there are also numerical errors which is happening in all the cases. These errors are causing inaccurate results on some small region in the model and even breaking the model altogether in some worse cases.

Keywords: large deformation, material point method, numerical simulation, slope stability

STUDI NUMERIK DEFORMASI BESAR PADA KELONGSORAN LERENG AKIBAT PEMBEBANAN MENGGUNAKAN METODE MATERIAL POINT

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ABSTRAK

Permasalah deformasi adalah masalah yang menantang untuk disimulasikan secara numerik. Dalam beberapa tahun terakhir pengembangan metode *Meshfree,* terutama Metode *Material Point*, menunjukkan progress yang cukup signifikan. Pada skripsi ini, akan dilakukan analisis permasalahan deformasi besar menggunakan metode *Material Point* ini untuk kasus kegagalan lereng akibat pembebanan. Oleh karena itu, dibuatlah sebuah model lereng secara hipotetis yang kemudian dianalisis terhadap variasi kekuatan tanah dan beban. Hasilnya dibagi menjadi dua yaitu analisis deformasi besar dan analisis deformasi kecil. Hasil analisis deformasi kecil kemudian dibandingkan dengan simulasi kasus serupa menggunakan metode elemen hingga. Sedangkan hasil analisis deformasi besar digunakan untuk memeriksa bentuk kegagalan lereng. Hasilnya menunjukkan bahwa analisis metode *Material Point* konsisten terhadap hasil analisis metode elemen hingga pada saat deformasi kecil. Sedangkan pada deformasi besar, metode *Material Point* dapat menunjukkan bentuk kegagalan sekaligus properti mekanis dari material yang dimodelkan. Akan tetapi, terdapat kesalahan numerik yang menyebabkan hasil pada beberapa area dalam model tidak akurat. Dalam beberapa kasus, kesalan ini bahkan menyebabkan simulasi gagal dilakukan.

Kata Kunci: deformasi besar, metode *material point*, simulasi numerik, kestabilan lereng

PREFACE

"in credo contendimus, in scio exploramus"`

In the beginning, God created everything with human as His highest creation. Since then, human kept learning and exploring the grandeur of God's created universe. And now, here I am, grateful for being blessed with the opportunity to study and explore a small chucks of it in my civil engineering study. Truly, by His grace alone, I'm able to complete this thesis on time. The topic of this thesis is "Numerical Study of Large Strain Deformation in Load Induced Slope Failure Using Material Point Method" and it is a partial requirement to graduate from Parahyangan University with Bachelor in Civil Engineering.

I want to express my utmost gratitude to my thesis advisor Aswin Lim, Ph.D. for the opportunity he opened for me to explore the topic of numerical simulations for geo-mechanical problems and for introducing me to my mentor, Ezra Y. S. (Tjung), Ph.D. who gave me the necessary guidance to learn in-depth into the topic. Furthermore, I wish to thanks to all the lecturers in *Pusat Studi Geoteknik Unpar* including Professor Paulus P. Rahardjo, Ignatius Tommy P., and Stefanus Diaz for their supports, motivation, and inspiration which keeps me excited with the field of geotechnical engineering. Moreover, special thanks to Reinard Primulando, Ph.D. and all faculty member in *Jurusan Fisika Unpar*, who let me join their classes and learn the supplementary courses needed for this thesis.

I also want to express my gratitude to my parents and my family for being a supportive family with my study, keep motivating me to do my best, and provide invaluable financial supports throughout my study. Thank you to my beloved girlfriend, Cindy Rosemary for her companion during the process of writing this thesis and throughout the hard time from the Covid Pandemic. Without all of them, it is hard to imagine for this thesis to be completed.

Thank also to my friends and colleagues in Unpar including: Mahitala Unpar, Unpar Choir, Greenate, and all the friends in civil engineering department for the exciting experience with them. The concerts with Unpar Choir and the journey in the nature with Mahilata Unpar will always be part of my memory as a bachelor student in Parahyangan Catholic University forever.

This thesis might not be perfect and there are so many rooms for improvements. For that, I highly appreciate any suggestions which might revamp this work. The experience to learn and to explore the glory of God's creation that this thesis has given is priceless for me. Thus, I hope this work will also be beneficial for all the readers out there.

Bandung, 12 January 2022

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LIST OF NOTATIONS

$\underline{\vec{a}}$	: Acceleration Matrix
$\partial\Omega_{\mathrm{T}}$	: Traction Boundary / Neumann Boundary
$\partial\Omega_{\mathrm{U}}$	: Displacement Boundary / Dirichlet Boundary
Ω_{el}	: Element Domain
$\underline{J}$	: Jacobian Matrix
V_{mp}	: Volume of a specific Material Point (also denotes by Ω_p)
$\vec{g}$	: Gravity Vector
$\vec{v}$	: Velocity Vector
w_q	: Weight of a specific Gaussian integration point
ε_v	: Volumetric Strain
FEM	: Finite Element Method
MP	: Material Points
MPM	: Material Point Method
t	: Time
Ω	: Material Domain
E	: Young's Modulus
$\boldsymbol{E}$	: Energy Field
c	: Cohesion
f, f^{int}, f^{ext}	: Forces, Internal Forces, External Forces
u	: Displacements
$\boldsymbol{N}$	: Interpolation Function
ε	: Strain Tensor
ν	: Poisson's Ratio
ρ	: Density

τ	: Tractions
ϕ	: Friction Angle
$\boldsymbol{\sigma}$	**:** Cauchy's Stress Tensor

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CHAPTER 1
INTRODUCTION

1.1 Background

Soil is a complex substance which properties are known for being very challenging to model numerically. These complexities could be addressed to soil heterogenous nature, its anisotropic characteristics, and its behavior variation across particle sizes and water contents. Moreover, when studied using constitutive models, soil behavior is highly non-linear. Meanwhile, the necessity to learn and to explore its potential is never higher as human civilization kept growing and developing.

The numerical approach to soil mechanics has been studied since Terzaghi in early 1900s. The assumptions to soil failure mechanism Terzaghi made (Terzaghi, 1943) could be acknowledged as the foundation of current geo-engineering practices along with the earliest numerical approach, the Limit Equilibrim Method (LEM). This approach is based on breaking down soil geometry and solving force equilibrium equations to evaluate its factor of safety. Current state-of-the-art method of geotechnical analyses are using a much more developed method known as the Finite Element Method (FEM). Unlike LEM, FEM solves the strain-stress equation and the continuum description of momentum balance equation. The difference of equations solved by FEM create the possibility of capturing soil deformations and applying time-history loads such as earthquakes and machines loads.

Though very successful, the standard Lagrangian FEM (UL-FEM) is known to suffer from severe mesh distortions if used to analyze large deformation problems with large strain which are common in soil failures. These inaccuracies lead to inaccurate results and on some occasions even lead to impossibility to simulate a complete failure phenomenon. To combat this problem, a relatively new method introduced by Sulsky et al. (1994) known as Material Point Method (MPM) is formulated and introduced.

MPM is a hybrid Eularian-Lagrangian method which can be seen as an extension of FEM. The differences are, in MPM, the body is dicretized into a set of material points (MP) and the mesh is only used to calculate the mechanics between these MPs on a fixed space domain. This method has been successful in various large deformation topics and its implementation have been done and developed by several research groups in various problems such as: landslides (Wang, B., 2017; Bhandari, T., et al., 2016; Yerro, A., 2015), penetrations (Beuth, L., 2013; Ceccato, F., et al., 2016), soil flow (Numada, M., et al., 2003; Kumar, K., 2015; Fern, J., 2016, 2017), and dam failures (Zabala, F. & Alonso, E. E., 2011; Martinelli, M., et al., 2017).

Because MPM is still relatively in its early development, MPM capabilities is still considered novel to the geotechnical engineering community. Thus, the main objective of this thesis is to investigate MPM capabilities to model failure mechanism. To achieve this purpose, a hypothetical slope is chosen to be modeled and analyzed. To discover MPM's accuracy, the slope will be subjected to incremental loadings until it fails. Then, the resulting simulation will be compared to the corresponding analysis done with current state-of-the-art method, The Finite Element Method. The same slope will also be subjected to an extreme load in order to investigate the failure process.

Figure 1.1 Holbeck Hall Landslide.
Source: BGS © UKRI

Slope stability problems are common geotechnical phenomena which includes the movement of soil mass due to the weight it holds exceeding its bearing capacity. These events could be very dramatic as a large mass of soil suddenly moves. Moreover, due to its hilly if not mountainous landscape, Indonesia is one of the countries which has the highest risk from these events. Therefore, the insights come from Material Point Method simulation might prove to be invaluable.

1.2 Problem Statements

The limitations of Finite Element Method in modelling large deformation drives a need to explore more advanced numerical techniques. One of the cases which involve large deformation is the slope stability problems. Thus, this thesis will try to utilize the capabilities of Material Point Method to simulate large strain deformation problems to simulate slope failure due to extreme loads and investigate its results in compared to the current common practice analysis results.

1.3 Research Objectives

The objectives of this research include:

1. Understanding the mechanism of failure in landslides due to extreme loads using MPM explicit formulation.
2. Comparing the results of MPM simulation to the FEM simulation results.
3. Investigating the role of time increments and damping ratio in the attempts to reach numerical convergent state.

1.4 Research Scopes

The scope of this research consists of:

1. 2D MPM model constructions of a hypothetical slope case along with its respective FEM model using PLAXIS 2D
2. MPM analysis using the code provided by CB-Geo Computational Geomechanics Research Group (Kumar et. al., 2019)

1.5 Methodology

The methods used to execute this research consist of these steps:

1. Literature Study

   On this step, information is collected from books, scientific journals, proceedings, theses, and dissertations written by previous researchers on the topic. This information is used to guide the whole process of the thesis including modeling, analysis, and interpretation.
2. Algorithm Writing for Model Generation and Discretization

   Here, an in-house Python code is developed to create model geometries, discretization schemes, and produce CB-Geo MPM input JSON and ASCII files.
3. Data Collection

   The data collected in the data collection method is secondary data. This includes but not limited to soil parameters, correlation charts, etc.
4. Numerical Simulation

   In the numerical simulation step, the soil parameter obtained from previous steps is inputted and the simulation is executed with both FEM and MPM.
5. Interpretation and Analysis

   Simulation results from MPM analysis is aggregated to its FEM counterparts and analyze to provide a better understanding and to create communicative graphs and figures.

1.6 Layout of The Thesis

This thesis is divided into 5 chapters as follows:

1. INTRODUCTION

   This chapter discuss the background of the problem presented and the statement of the problems. This chapter also includes the objective of the research, its scope, methodology, thesis layout, and research flow diagram.
2. LITERATURE STUDY

   In this chapter, a comprehensive literature study on the topics in this thesis is discussed. The topics will cover especially MPM formulation for single point one phase approach, theory of constitutive models, and time-history loading.
3. RESEARCH METHODOLOGY

   In the methodology chapter, an in-depth procedure of each numerical simulations is explained in detail. Here also provided the method used to interpret and analyze the data obtained from the simulations.
4. DATA ANALYSIS

   This chapter will discuss the simulation results and its interpretation including the tunings needed for the parameters, the differences of the results from different soil constitutive models, error magnitude, and calculation results.
5. CONCLUDING REMARKS

   Finally, all works will be summarized in this final chapter along with some remarks such as problems revealed in the research and future developments.

1.7 Research Flow Diagram

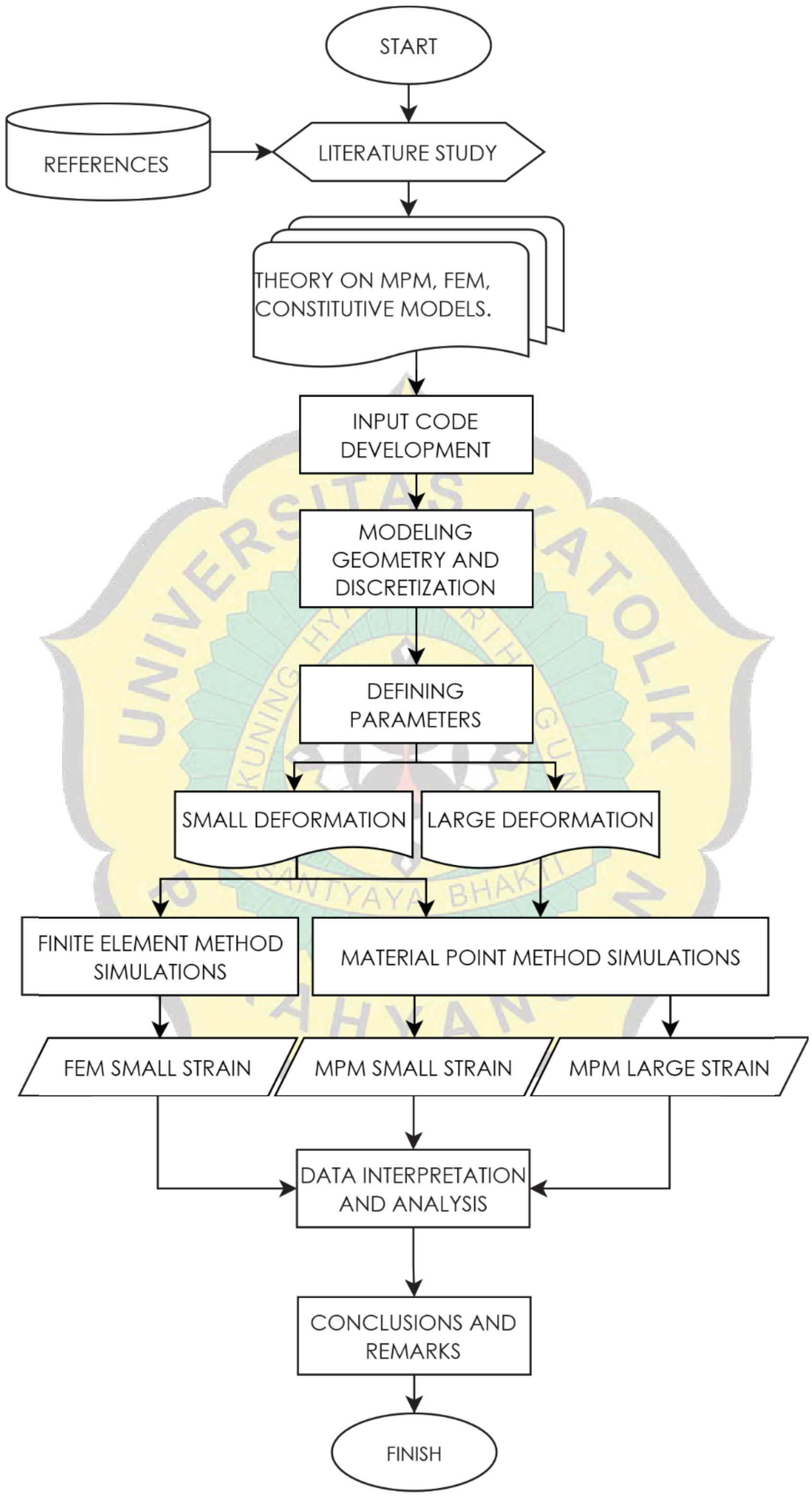

Figure 1.2 Research flow Diagram