

# MPM-Geomechanics Manual

An open-source Material Point Method code for geomechanics.

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## 1 Introduction to the Material Point Method (MPM)

The Material Point Method is an hybrid Lagrangian-Eulerian numerical method, that allows for simulating continuum mechanics processes involving large deformations and displacements without issues related to computational mesh distortion. In MPM, the material domain to be simulated is discretized into a set of material points that can move freely within a computational mesh, where the equations of motion are solved. The material points store all variables of interest during the simulation, such as stress, pore pressure, temperature, etc., giving the method its Lagrangian characteristic.

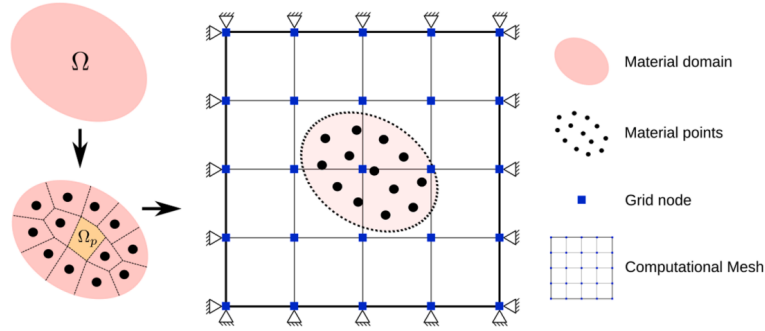


Figure 1: General MPM approach. Solid and space discretization with Lagrangian material points and structured Eulerian mesh.

In an MPM computational cycle, all variables stored in the material points are computed at the computational mesh nodes using interpolation functions, and then the equation of motion is solved at the nodes. The nodal solution obtained is interpolated back to the particles, whose positions are updated, and all nodal variables are discarded. This method, enables the numerical solution of the motion equation in continuum mechanics by using the nodes of an Eulerian mesh for integration and Lagrangian material points to transfer and store the properties of the medium.

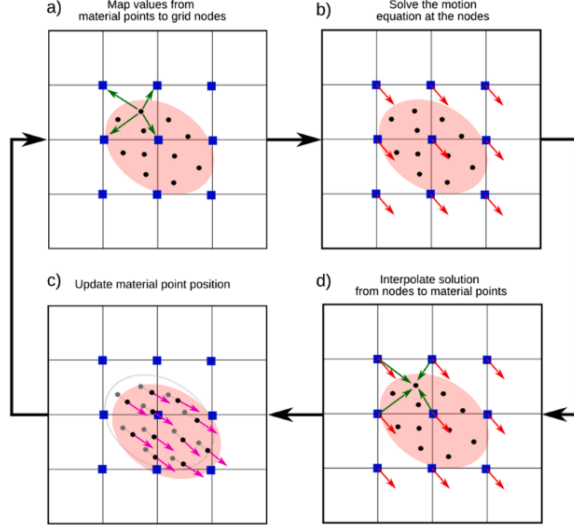


Figure 2: MPM computational cycle

## 2 MPM Formulation

The material point method formulation is based on the continuum mechanics motion equation in 3D:

$$\frac{\partial \sigma_{ij}}{\partial x_j} + \rho b_i = \rho a_i \quad (1)$$

The internal forces are related with the  $\sigma_{ij}$ , the Cauchy stress tensor,  $\rho$  is the mass density,  $b_i$  is a body force and  $a_i$  is the acceleration.

The equation 1 is presented here in tensor notation, but, vector and matrix can be equally used. The discrete form of the motion equation can be obtained using the weak form of this partial differential equation. The weak form is obtained by multiplying the motion equation by arbitrary weighting functions and integrating this product over the domain. In this procedure, the integration by parts reduces the order the stress tensor and introduces the natural boundary conditions:

$$-\int_{\Omega} \sigma_{ij} \delta u_{i,j} dV + \int_{\Gamma} t_i \delta u_i dA + \int_{\Omega} \rho b_i \delta u_i dV = \int_{\Omega} \rho a_i \delta u_i dV \quad (2)$$

Here  $\delta u_i$  are arbitrary displacements functions, whose value in the boundary are  $\delta u_i|_{\Gamma} = 0$  and  $t_i$  is an external traction acting on the boundary  $\Gamma$ .

In the MPM context any field or space property  $f(x_i)$  can approximated using the value stored in the particle  $f_p$ :

$$f(x_i) = \sum f_p \chi_p(x_i)$$

where  $\chi_p$  is the particle characteristic function that defines the volume occupied by the material point:

$$V_p = \int_{\Omega_p \cap \Omega} \chi_p(x_i) dV$$

In consequent, density, acceleration and stress fields can be approximated by the values stored in particles:

$$\rho(x_i) = \sum_p \frac{m_p}{V_{ip}} \chi_p(x_i) \rho(x_i) a_i(x_i) = \sum_p \frac{\dot{p}_{ip}}{V_p} \chi_p(x_i) \sigma_{ij}(x_i) = \sum_p \sigma_{ijp} \chi_p(x_i)$$

where  $\dot{p}_{ip} = m_p \dot{v}_{ip} = m_p a_{sip} = f_{ip}$  is the momentum variation in time that is equal to the total force, regarding the second Newton's law.

Replacing these fields in the weak form of the motion equation we have:

$$-\sum_p \int_{\Omega_p \cap \Omega} \sigma_{ijp} \chi_p \delta u_{i,j} dV + \int_{\Gamma} t_i \delta u_i dA + \sum_p \int_{\Omega_p \cap \Omega} \frac{m_p}{V_p} b_{ip} \chi_p \delta u_i dV = \sum_p \int_{\Omega_p \cap \Omega} \frac{\dot{p}_p}{V_p} \chi_p a_i dV$$

In the generalized interpolation material point method (GIMP), the resolution of this equation is carried out using a Petrov–Galerkin scheme where the characteristic functions  $\chi_p(x_i)$  are the trial functions and the nodal interpolation functions  $N_I(x_i)$  are the test functions. To arrive at this scheme, the virtual displacements are expressed using nodal interpolation functions:

$$\delta u_i = \sum_I N_{Ip} \delta u_{iI}$$

The trial and test functions are such that:

$$\sum_I N_I(x_i) = 1 \quad \sum_p \chi_p(x_i) = 1$$

The resulting discrete form of the motion equation then is:

$$f_{iI}^{int} + f_{iI}^{ext} = \dot{p}_{iI}$$

where

$$p_{iI} = \sum_p S_{Ip} p_{Ip}$$

is the nodal momentum,

$$f_{iI}^{int} = - \sum_p \sigma_{ijp} S_{Ip,j} V_p$$

is the nodal internal force, and

$$f_{iI}^{ext} = \sum_p m_p S_{Ip} b_{ip} + \int_{\Gamma} t_i N_I(x_i) dA$$

is the external force at node  $I$ .

The function  $S_{Ip}$  and its gradients  $S_{Ip,j}$  are the weighting functions of node  $I$  evaluated at the position of particle  $p$ .

The GIMP shape functions are defined by

$$S_{Ip} = \frac{1}{V_p} \int_{\Omega_p \cap \Omega} \chi_p(x_i) N_I(x_i) dV$$

and

$$S_{Ip,j} = \frac{1}{V_p} \int_{\Omega_p \cap \Omega} \chi_p(x_i) N_{I,j}(x_i) dV$$

These two functions are also a partition of the unity  $\sum_I S_{Ip} = 1$ .

The weighting function need to be integrated over the particle domain by choosing different characteristic functions and interpolation functions in a Petrov–Galerkin scheme. In the contiguous particle GIMP (cpGIMP) the characteristic function is defined as step function and the interpolation function is defined as linear function:

$$\chi_p(x) = \begin{cases} 1, & x \in \Omega_p, \\ 0, & x \notin \Omega_p. \end{cases}$$

$$N_I(x) = \begin{cases} 0, & |x - x_I| \geq L, \\ 1 + \frac{x - x_I}{L}, & -L < x - x_I \leq 0, \\ 1 - \frac{x - x_I}{L}, & 0 < x - x_I < L. \end{cases}$$

Where the integration is performed analytically within the particle domain.

$$S_{Ip} = \begin{cases} 0 & |\xi| \geq L + l_p \\ (L + l_p + \xi)^2 / 4Ll_p & -L - l_p < \xi \leq -L + l_p \\ 1 + \xi/L & -L + l_p < \xi \leq -l_p \\ 1 - (\xi^2 + l_p^2) / 2Ll_p & -l_p < \xi \leq l_p \\ 1 - \xi/L & l_p < \xi \leq L - l_p \\ (L + l_p - \xi)^2 / 4Ll_p & L - l_p < \xi \leq L + l_p \end{cases}$$

and

$$\nabla S_{Ip} = \begin{cases} 0 & |x_p - x_I| \geq L + l_p, \\ \frac{L + l_p + (x_p - x_I)}{2Ll_p} & -L - l_p < x_p - x_I \leq -L + l_p, \\ \frac{1}{L} & -L + l_p < x_p - x_I \leq -l_p, \\ -\frac{x_p - x_I}{Ll_p} & -l_p < x_p - x_I \leq l_p, \\ -\frac{1}{L} & l_p < x_p - x_I \leq L - l_p, \\ -\frac{L + l_p - (x_p - x_I)}{2Ll_p} & L - l_p < x_p - x_I \leq L + l_p. \end{cases}$$

In which  $2l_p$  is the particle domain,  $L$  is the mesh size in 1D, and  $\xi$  is the relative particle position to node. Weighting functions in 3D are obtained by the product of three one-dimensional weighting functions:

$$S_{Ip}(x_{ip}) = S_{Ip}(\xi)S_{Ip}(\eta)S_{Ip}(\zeta)$$

where  $\xi = x_p - x_I$ ,  $\eta = y_p - y_I$  and  $\zeta = z_p - z_I$ .

### 3 Explicit MPM integration

The discrete form of the motion equation needs to be integrated in time for obtaining the solution in time  $t^{n+1}$ . The displacement, the velocity and the acceleration at time  $t^0, t^1, t^2, \dots, t^n$  are known, and the values at time  $t^{n+1}$  are required, namely the solution of the problem. The time integration can be done by explicit and implicit methods. In explicit method, the solution  $t^{n+1}$  is obtained only with the current information  $f(t^n, \dots, t^0)$ . In implicit method the solution needs to solve a system due the solution is in function of the form  $f(t^{n+1}, \dots, t^0)$ .

#### 3.1 Central difference Method

In central difference method, the velocity at  $t^{n+1/2}$  can be approximated as:

$$\dot{u}^{n+1/2} = (u^{n+1} - u^n)\Delta t$$

and, the acceleration in  $t^n$  can be approximated as:

$$\ddot{u}^n = (\dot{u}^{n+1/2} - \dot{u}^{n-1/2})\Delta t$$

and therefore, the required displacement at  $t^{n+1}$  can be calculated as:  $u^{n+1} = u^n + \dot{u}^{n+1/2} \Delta t$ , where the velocity is

$$\dot{u}^{n+1/2} = \dot{u}^{n-1/2} + \ddot{u}^n \Delta t$$

The motion equation in time  $t^n$  is  $m \ddot{u}^n = f^n$ , therefore the acceleration in time  $t^n$  is  $\ddot{u}^n = f^n/m$ . Using this acceleration equation in the  $\dot{u}^{n+1/2}$  we have the velocity  $\dot{u}^{n+1/2}$ :

$$\dot{u}^{n+1/2} = \dot{u}^{n-1/2} + f^n/m \Delta t$$

## 4 Numerical implementation of central difference method

For one  $\Delta t$ , the updated position can be obtained as:

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**Algorithm 1** Explicit time integration

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- 1: Compute forces  $f^n$
  - 2: Compute acceleration  $\ddot{u}^n = f^n/m$
  - 3: Update velocity  $\dot{u}^{n+1/2} = \dot{u}^{n-1/2} + \ddot{u}^n \Delta t$
  - 4: Update position  $u^{n+1} = u^n + \dot{u}^{n+1/2} \Delta t$
  - 5:  $n \leftarrow n + 1$
- 

## 5 Stability Requirement

The central difference method is explicit here and conditionally stable, so the time step must be less than a certain value for avoiding error amplification. For linear systems this critical time step value depends on the natural period of the system. For undamped linear systems the critical time step is:  $\Delta t_{cr} = T_n/\pi$ , where  $T_n$  is the smallest natural period of the system. For finite element method, the critical time step of the central difference method can be expressed as:

$$\Delta t_{cr} = \min_e(l^e/c)$$

Where  $l^e$  is the characteristic length of the element and  $c$  is the sound speed. This time step restriction implies that time step has to be limited such that a disturbance, a mechanical wave, can travel across the smallest characteristic element length within a single time step.

This condition is known as CFL condition, or Courant-Friedrichs-Lewy condition. For linear elastic material the sound speed (compression P wave) is:

$$c = \sqrt{\frac{E(1-\nu)}{(1+\nu)(1-2\nu)\rho}}$$

In the MPM, the particles can have velocities in any time step, so the critical time speed can be written with this velocity plus:

$$\Delta t_{cr} = l^e / \max_p(c_p + |v_p|)$$

In a structured regular mesh,  $l^e$  is the grid cell dimension. And  $c_p$  is the sound speed calculated with the material parameters stored in particles.

## 6 Numerical damping

Real materials dissipates energy during movement. Temperature and plastic deformation are common sources of energy dissipation. In numerical analysis numerical damping can be used for obtaining the quasi-static condition of the dynamic system.

## 7 Local damping

The numerical damping is a technique for getting a stationary solution of the dynamic system. In the MPM-Geomechanics simulator we have two type of numerical damping: the local (viscous) and the kinetic (dynamic relaxation) damping.

## 8 Quasi-static solution with local damping

The local damping is used to get a quasi-static solution of the dynamic system using a viscous nodal force. In each time step, a viscous force is applied in each node, whose magnitude is proportional and opposite to the nodal velocity.

$$f_{iI}^{dnplocal} = -\alpha |f_{iI}^{unb}| \hat{v}_{iI}$$

, where the unbalanced nodal force is:

$$f_{iI}^{unb} = f_{iI}^{int} + f_{iI}^{ext}$$

Therefore, the resulting discrete form of the motion equation with viscous nodal damping is:

$$\dot{p}_{iI} = f_{iI}^{int} + f_{iI}^{ext} + f_{iI}^{dnplocal}$$

## 9 Explicit algorithm

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### Algorithm 2 Explicit MPM integration scheme

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- 1: Compute nodal mass:  $m_I^k = \sum_{p=1}^{n_p} m_p N_{Ip}^k$
  - 2: Compute nodal momentum:  $p_{iI}^{k-1/2} = \sum_{p=1}^{n_p} m_p v_{ip}^{k-1/2} N_{Ip}^k$
  - 3: Update seismic velocities from record (if required):
 
$$a_i^{s, k-\frac{1}{2}} = a_i^{s, \text{record}}$$

$$v_i^{s, k+\frac{1}{2}} = \sum_{l=0}^{l=1-\frac{1}{2}} v_i^{s, l} + a_i^{s, \text{record}} \Delta t$$
  - 4: Impose nodal momentum boundary conditions:  $p_{iI}^{k-1/2} = 0$  (fixed condition)
  - 5: Compute internal forces:  $f_{iI}^{intk} = -\sum_{p=1}^{n_p} \sigma_{ij}^p S_{Ip,j}^k V_p$
  - 6: Compute external forces:  $f_{iI}^{extk} = \sum_{p=1}^{n_p} m_p b_i S_{Ip}^k + \int_{\Gamma} t_i N_I(x_i) dA$
  - 7: Compute nodal unbalanced forces:  $f_{iI}^{unbk} = f_{iI}^{intk} + f_{iI}^{extk}$
  - 8: Compute damping forces (if required):  $f_{iI}^{dnpk} = -\alpha |f_{iI}^{unbk}| \hat{v}_{iI}^{k-1/2}$
  - 9: Compute total nodal forces:  $f_{iI}^{totk} = f_{iI}^{unbk} + f_{iI}^{dnpk}$
  - 10: Impose nodal force boundary conditions:  $f_{iI}^{totk} = 0$  (fixed condition)
  - 11: Update nodal momenta:  $p_{iI}^{k+\frac{1}{2}} = p_{iI}^{k-1/2} + f_{iI}^{totk} \Delta t$
  - 12: Update particle velocities:  $v_{ip}^{k+\frac{1}{2}} = v_{ip}^{k-1/2} + \sum_{I=1}^{n_n} \frac{f_{iI}^{totk}}{m_I^k} N_{Ip}^k \Delta t$
  - 13: Seismic nodal velocity:  $v_{iI}^{k+\frac{1}{2}} = v_i^{s, k+\frac{1}{2}}$
  - 14: Contact correction (if required):  $v_{ip}^{k+\frac{1}{2}} = STLContactCorrection(v_{ip}^{k+\frac{1}{2}})$
  - 15: Update particle positions:  $x_{ip}^{k+1} = x_{ip}^k + \sum_{I=1}^{n_n} v_{iI}^{k+\frac{1}{2}} N_{Ip}^k \Delta t$
  - 16: For MUSL scheme, recalculate nodal momentum:  $p_{iI}^{k+1/2} = \sum_{p=1}^{n_p} m_p v_{ip}^{k+1/2} N_{Ip}^k$
  - 17: Impose nodal momentum boundary conditions:  $p_{iI}^{k+1/2} = 0$  (fixed condition)
  - 18: Calculate nodal velocities:  $v_{iI}^{k+1/2} = p_{iI}^{k+1/2} / m_I^k$
  - 19: Compute particle strain increment:  $\Delta \varepsilon_{ij}^{p, k+1/2} = \frac{1}{2} (N_{p,j}^k v_i^{k-1/2} + N_{p,i}^k v_j^{k+1/2}) \Delta t$
  - 20: Compute vorticity increment:  $\Delta \omega_{ij}^{p, k+1/2} = \frac{1}{2} (N_{p,j}^k v_i^{k+1/2} - N_{p,i}^k v_j^{k+1/2}) \Delta t$
  - 21: Update particle density:  $\rho_p^{k+1} = \rho_p^k / (1 + \text{tr}(\Delta \varepsilon_{ijp}^{k-1/2}))$
  - 22: Update particle stress:  $\sigma_{ij}^{p, k+1} = StressUpdate(\sigma_{ij}^{p, k}, \Delta \varepsilon_{ij}^{p, k-1/2}, \Delta \omega_{ij}^{p, k-1/2})$
  - 23:  $k \leftarrow k + 1$
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## 10 Project data structure

The directories with files and folders in this project are organized as follows:

- `src/` `build/` `qa/` `external/` and `inc/` sources, builds qa(tests and benchmarking), google-test folder and C++ headers files
- `manual/` `docs/` program manual and documentation for doxygen
- `tests/` simulation results of analytical and numerical tests
- `examples/` application examples

## 11 Build commands

The following instructions outline the steps required to build the MPM-Geomechanics project.

### 11.1 Instruction commands using Linux/WSL or MSYS2 MINGW64 console line

After cloning the repository, navigate to the project directory and execute the following commands:

```
1 cd build/CMake
2 cmake -S . -B build -DCMAKE_BUILD_TYPE=Release
3 cmake --build build -j
```

### 11.2 Compilation in Windows

Prior to proceeding with these instructions, please consult the windows required programs section in this manual.

The simplest way to compile on windows is by using the `‘bash’` file at `‘/build/CMake’` with `‘MSYS2 MINGW64’` console line, just execute:

```
1 cd project-directory/build/CMake
2 ./cmake-build.bash
```

Alternatively, you can use the following commands:

```
1 cd project-directory/build/CMake
2 cmake -G "Unix Makefiles" -B build
3 cmake --build build
```

### 11.3 Compiling on Linux

Prior to proceeding please consult the Linux Required Programs section in this manual.

The simplest way to compile on Linux is by using the `‘bash’` file at `‘/build/CMake’`, just execute:

```
1 cd build/CMake
2 ./cmake-build.bash
```

Alternatively, you can use the following commands:

```
1 cd build/CMake
2 cmake -G "Unix Makefiles" -B build
3 cmake --build build
```



## 12 Visual Studio Solution

For compiling the code in windows you can use the Visual Studio solution file ‘/build/MPM-Geomechanics.sln’, and build it by pressing ‘Ctrl+B’. Alternatively you can compile it by using command in a \*Developer Command Prompt\*:

```
1 msbuild MPM-Geomechanics.sln -p:Configuration=Release
```

## 13 Make Compilation

For compile the code in a linux environment, execute the makefile inside the make folder:  
MPM-Geomechanics/build/make/makefile.

## 14 Program features

The MPM-Geomechanics program is an open source implementation of the Material Point Method (MPM) for geomechanics applications. It is designed to simulate the behavior of soils and rock under various loading conditions, including static and dynamic loads.

The main features of the program are:

- three dimensional formulation
- dynamic formulation
- shared memory parallelization using OpenMP
- body-based (pre-defined bodies, particles-list)
- constitutive models for soil and rock materials
- softening/hardening models to represent weakness during large deformations
- frictional contact algorithm using STL surfaces
- coupled fluid-mechanical formulation (\*under development\*)
- seismic boundary conditions

## 15 Compiled binaries

The recommended way to get the compiled binaries is by downloading the artifacts from the latest GitHub Actions workflow run.

- go to the [Actions page](https://github.com/fabricix/MPM-Geomechanics/actions).
- elect the latest run of the **MSBuild** workflow for Window, or **CI** for Linux.
- at the bottom, you will find the available artifacts under the **Artifacts** section.
- download the ‘compiled-binaries’ artifact to get the compiled code.

## 16 Required Programs

The following instructions outline the steps required to install all necessary programs to build the MPM-Geomechanics project and execute its test suite.

## 16.1 Required Programs - Windows

For Windows installation, the required programs can be installed using Winget and MSYS2. The following table summarizes the required programs, their installation methods, and the corresponding commands.

Program	Installation	Command
<b>Winget</b>	Microsoft's official website	Native of Windows
<b>Git</b>	via Winget	<code>winget install -e -id Git.Git</code>
<b>MSYS2</b>	via Winget	<code>-e -source winget</code> <code>winget install -e -id</code> <code>MSYS2.MSYS2 -source winget</code>
<b>GitHub CLI</b>	via MSYS2 MINGW64	<code>pacman -S</code> <code>mingw-w64-x86_64-github-cli</code>
<b>Python</b>	via MSYS2 MINGW64	<code>pacman -S</code> <code>mingw-w64-x86_64-python</code>
<b>CMake</b>	via MSYS2 MINGW64	<code>pacman -S</code> <code>mingw-w64-x86_64-cmake</code>
<b>GCC</b>	via MSYS2 MINGW64	<code>pacman -S mingw-w64-x86_64-gcc</code>
<b>G++</b>	via MSYS2 MINGW64	<code>pacman -S mingw-w64-x86_64-gcc</code>
<b>Make</b>	via MSYS2 MINGW64	<code>pacman -S make</code>

Table 1: Programs required for Windows installation.

### Pre-requisite: Verify Winget installation

**Make sure you have Winget installed.** You can verify this by running `winget -version`.

If you don't have Winget installed, you can get it from Microsoft's official website.

### Step 1: Install Git, GitHub, and MSYS2

Run the following commands:

```
1 winget install -e --id Git.Git -e --source winget
2 winget install -e --id MSYS2.MSYS2 --source winget
```

### Step 2: Install required packages in MSYS2 MINGW64

```
1 pacman -S mingw-w64-x86_64-github-cli
2 pacman -S mingw-w64-x86_64-python
3 pacman -S mingw-w64-x86_64-cmake
4 pacman -S mingw-w64-x86_64-gcc
5 pacman -S make
```

### Step 3: Verify the installations

```
1 git --version
2 gh --version
3 python --version
4 cmake --version
5 make --version
6 gcc --version
7 g++ --version
```

## 16.2 Required Programs - Linux

For Linux installation, the required programs can be installed using the apt package manager. The following table summarizes the required programs, their installation methods, and the corresponding commands.

Program	Installation	Command
Git	via apt	<code>sudo apt install git</code>
GitHub CLI	via apt	<code>sudo apt install gh</code>
Python	via apt	<code>sudo apt install python3 python3-pip</code>
CMake	via apt	<code>sudo apt install cmake</code>
GCC	via apt	<code>sudo apt install build-essential</code>
G++	via apt	<code>sudo apt install build-essential</code>
Make	via apt	<code>sudo apt install build-essential</code>

Table 2: Programs required for Linux installation.

### Step 1: Install all packages via apt

Listing 1: Installing required packages using *apt*

```
1  sudo apt install git
2  sudo apt install gh
3  sudo apt install python3 python3-pip
4  sudo apt install cmake
5  sudo apt install build-essential
```

### Step 2: Verify the installations

```
1  git --version
2  gh --version
3  python3 --version
4  cmake --version
5  make --version
6  gcc --version
7  g++ --version
```

## 17 Code documentation

Code documentation is generated using Doxygen documentation generator. To generate the documentation run the following command:

```
1  doxygen Doxyfile
```

The HTML generated documentation is located in `./docs/index.html`.

## 18 Execution

In order to run simulations in several terminal, you can add the compiled code in the system `'PATH'`.

For Windows, you can follow these steps:

- Open the Start Search, type in "env", and select "Edit the system environment variables"

- In the System Properties window, click on the "Environment Variables..." button.
- In the Environment Variables window, under the "System variables" section, find and select the "Path" variable, then click on the "Edit..." button.
- In the Edit Environment Variable window, click on the "New" button and add the path to the folder where the compiled binary is located (e.g., `C:\path\to\MPM-Geomechanics\build\CMake\build\Release`).
- Click "OK" to close all windows.

For Linux, you can add the following line to your `~/.bashrc` or `~/.bash_profile` file:

```
1 export PATH=$PATH:/path/to/MPM-Geomechanics/build/CMake/build
```

For both Windows and Linux, after adding the path, you can open a new terminal and run the program from any location by simply typing 'MPM-Geomechanics' followed by the input file name.

## 19 Testing Compilation and Benchmarking

In order to compile the testing and benchmarking executables, please follow the instructions below.

### 19.1 How to Compile

Prior to proceeding with these instructions, please consult required programs in manual.

The tests use **GoogleTest**. It is necessary to import this library by cloning the official repository into the folder `/external`. Each developer must clone this repository independently.

```
1 cd external
2 git clone https://github.com/google/googletest.git
```

The simplest way to compile on Windows and Linux is by using the `.bash` file at `/build/qa` with `MSYS2 MINGW64` console line, simply execute the following command in the directory `MPM-Geomechanics/build/qa`:

```
1 ./cmake-build.bash
```

Alternatively, you can use the following commands:

```
1 cmake -G "Unix Makefiles" -B build
2 cmake -G "Unix Makefiles" -B build
3 cmake --build build
```

These commands will generate two executables: `MPM-Geomechanics-tests` and `MPM-Geomechanics-benchmark`.

- `MPM-Geomechanics-tests`: Run testing using GoogleTest. All files ending with `.test.cpp` are testing files, you can find them in the directory `qa/tests`.

- `MPM-Geomechanics-benchmark`: Run benchmark using GoogleTest. All files ending with `.benchmark.cpp` are performance files. You can find them in the directory `qa/benchmark`.

### 19.2 How does benchmarking work?

If you are using Windows OS, make sure to use the MINGW64 command-line console.

### 19.3 Executable MPM-Geomechanics-benchmark

To run the benchmark correctly, a JSON file named `benchmark-configuration.json` is required. This file allows the user to specify values for each test. If the file does not exist or a value is missing, a default value will be used.

The executable `MPM-Geomechanics-benchmark` allows the following command-line arguments:

**<directory>**: Specifies which file should be used to run the benchmark. If no file is specified, the program will use `benchmark-configuration.json` located in the same directory as the executable. Example: `MPM-Geomechanics-benchmark configuration-file.json`

The executable `MPM-Geomechanics-benchmark` allows the following command-line flags:

**-log**: Shows more information about missing keys in the `benchmark-configuration.json` file

### 19.4 Script (executable): start-multi-benchmark.py

The performance test can also be executed using the `start-multi-benchmark.py` script, which allows running benchmarks with one or more executables downloaded as artifacts from GitHub and stores the log results in separate folders. Each executable is automatically downloaded from GitHub as an artifact, using an ID specified in `start-multi-benchmark-configuration.json`.

Additionally, the benchmark configuration (number of martial points and number of threads) can be defined in the same file.

Example of a `start-multi-benchmark-configuration.json` file:

```
1 {
2   "executables": {
3     "win_benchmark_executable": "MPM-Geomechanics-benchmark.exe", ->
        An executable located at build/qa/MPM-Geomechanics-benchmark.
        exe
4     "win_github_id": "17847226555" -> An artifact ID that represent
        it. can check out if it exists via gh run view <ID>
5   },
6   "parameters": {
7     "particles": [ 15000, 25000, 50000], -> material point to test
8     "threads": [1, 5, 10] -> number of threads to test
9   }
10 }
```

This setup will run 3x3 (particles x threads) totaling 18 tests (3x3x2). The executable `start-multi-benchmark.py` allows the following command-line flags:

- `--clear`: Removes the `**benchmark folder**` (if it exists) before executing the performance tests.
- `--cache`: Uses the previously created cache instead of the `start-multi-benchmark-configuration.json` file.

## 20 Verification Problems

Verification problems are designed to verify and to show some new program functionality.

### 20.1 Boussinesq's Problem

#### Introduction

In Geomechanics, the Boussinesq's problem refers to the point load acting on a surface of an elastic half-space. The boundary conditions for this problem are:

- The load  $P$  is applied only at one point, at the origin.
- The load is zero at any other point.
- For any point infinitely distant from the origin, the displacements must all vanish.

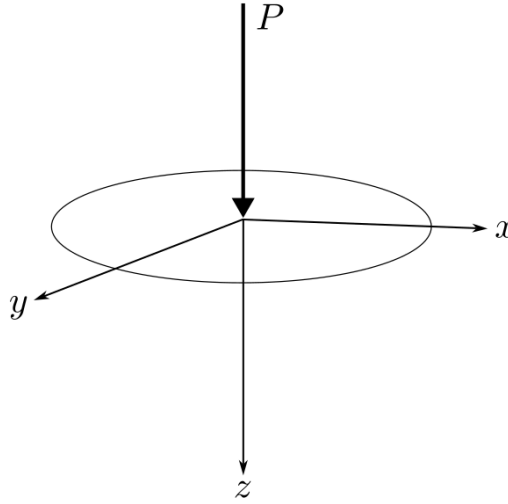


Figure 3: Boussinesq's problem.

#### Analytical Solution

The analytical solution of the vertical displacement field is:

$$u_z(x, y, z) = \frac{P}{4\pi Gd} \left( 2(1 - \nu) + \frac{z^2}{d^2} \right)$$

where  $G = \frac{E}{2(1+\nu)}$  is the shear modulus of the elastic material,  $\nu$  is the Poisson ratio, and  $d = \sqrt{x^2 + y^2 + z^2}$  is the total distance from the load to the point.

#### MPM Model and Result Comparison

To model the displacement field generated by the point load, we create an elastic body with dimensions  $l_x = l_y = l_z = 1$  m, using the keyword "cuboid" with Point 1 at (0,0,0) and Point 2 at (1,1,1).

For the elastic parameters:

$$E = 200 \times 10^6 \text{ Pa}, \quad \rho = 1500 \text{ kg/m}^3, \quad \nu = 0.25$$

The computational mesh has cell dimensions  $\Delta x = \Delta y = \Delta z = 0.1$  m. A nodal load of magnitude 1 is applied in the vertical direction at the midpoint of the upper surface. The plane  $Z_n$  is free, while all other planes are sliding (only tangential displacements allowed). Dynamic relaxation is used to reach a static solution, through the keyword "damping" with type "kinetic".

## Input File

```

1  {
2    "body": {
3      "elastic-cuboid-body": {
4        "type": "cuboid",
5        "id": 1,
6        "point_p1": [0.0, 0.0, 0],
7        "point_p2": [1, 1, 1],
8        "material_id": 1
9      }
10   },
11   "materials": {
12     "material-1": {
13       "type": "elastic",
14       "id": 1,
15       "young": 200e6,
16       "density": 1500,
17       "poisson": 0.25
18     }
19   },
20   "mesh": {
21     "cells_dimension": [0.1, 0.1, 0.1],
22     "cells_number": [10, 10, 10],
23     "origin": [0.0, 0.0, 0.0],
24     "boundary_conditions": {"plane_Zn": "free"}
25   },
26   "time": 0.025,
27   "time_step_multiplier": 0.3,
28   "nodal_point_load": [[[0.5, 0.5, 1.0], [0.0, 0.0, -1.0]]],
29   "damping": {"type": "kinetic"}
30 }

```

The MPM numerical results show good agreement with the analytical solution, with small deviations due to discretization and the representation of the domain by particles with finite volume. Errors decrease with mesh refinement.



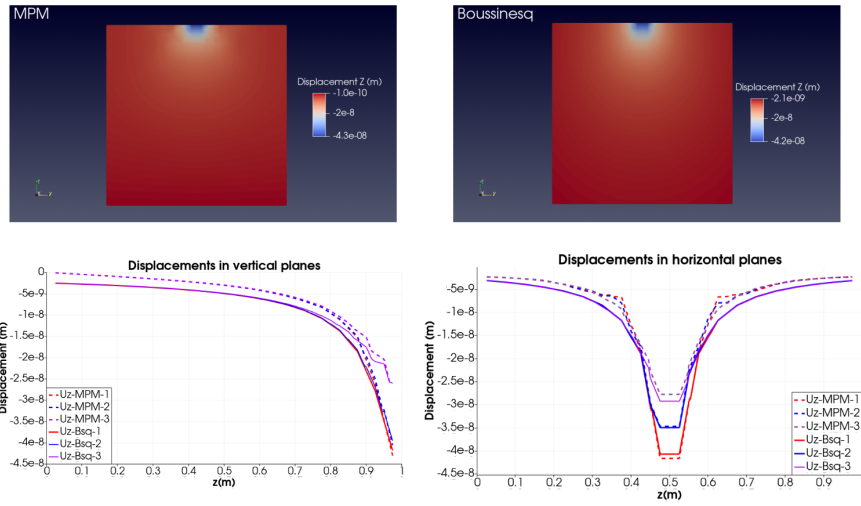


Figure 4: Comparison between analytical and MPM results.

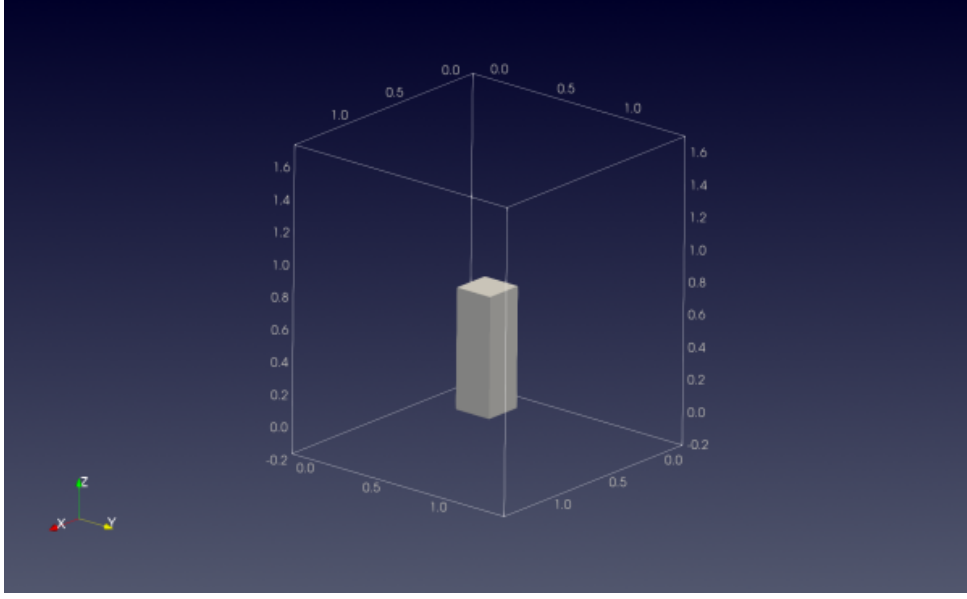


Figure 5: Geometry of the elastic body.

## 20.2 Base Acceleration Example

### Introduction

In this example we model the motion of an elastic body subjected to a dynamic boundary condition. The body is a cuboid with dimensions  $l_x = l_y = 0.3$  m and  $l_z = 0.8$  m, with lower coordinate point  $p_{min} = (0.4, 0.4, 0.0)$  m.

The base acceleration is defined as:

$$\ddot{u} = A 2\pi f \cos(2\pi f t + \alpha)$$

The total simulation time is  $T = 2$  s, with a time step  $\Delta t = 10^{-4}$  s. Material properties:

$$\rho = 2500 \text{ kg/m}^3, \quad E = 100 \times 10^6 \text{ Pa}, \quad \nu = 0.25$$

### MPM Model

The MPM model consists of uniformly distributed particles inside the body, created with the keywords "body" and "cuboid". The mesh dimensions are  $\Delta x = \Delta y = \Delta z = 0.1$  m, and it covers the full expected displacement range of the body. The mesh uses  $n_x = 12, n_y = 12, n_z = 15$ .

### Input File

```

1  {
2    "stress_scheme_update": "USL",
3    "shape_function": "GIMP",
4    "time": 10,
5    "time_step": 0.0005,
6    "gravity": [0.0, 0.0, 0.0],
7    "n_threads": 1,
8    "damping": {
9      "type": "local",
10     "value": 0.0
11   },

```

```

12     "results": {
13         "print": 100,
14         "fields": ["id", "displacement", "velocity", "material", "active", "body
15             "]
16     },
17     "n_phases": 1,
18     "mesh": {
19         "cells_dimension": [0.1, 0.1, 0.1],
20         "cells_number": [10, 10, 15],
21         "origin": [0, 0, 0]
22     },
23     "earthquake": {
24         "active": true,
25         "file": "base_acceleration.csv",
26         "header": true
27     },
28     "material": {
29         "elastic_1": {
30             "type": "elastic",
31             "id": 1,
32             "young": 10e6,
33             "density": 2500,
34             "poisson": 0.25
35         }
36     },
37     "body": {
38         "columns_1": {
39             "type": "cuboid",
40             "id": 1,
41             "point_p1": [0.2, 0.2, 0],
42             "point_p2": [0.5, 0.5, 1.0],
43             "material_id": 1
44         }
45     }

```

## Earthquake Block Parameters

```

1     "earthquake": {
2         "active": true,
3         "file": "base_acceleration.csv",
4         "header": true
5     }

```

Where:

- **active:** Enables or disables seismic loading.
- **file:** Path to the CSV file containing time, acceleration\_x, acceleration\_y, and acceleration\_z.
- **header:** True if the CSV has a header row.

Example of the first lines of the record:

```

1     t,ax,ay,az
2     0.0,-1.8849555921538759,-0.9424777960769379,-0.0
3     5e-05,-1.8849554991350466,-0.9424777844495842,-0.0

```

```

4  0.0001, -1.884955220078568, -0.9424777495675233, -0.0
5  0.00015000000000000001, -1.8849547549844674, -0.9424776914307561, -0.0
6  ...

```

## Post-processing (results and visualizations)

Particle results are found in the `/particle` folder and grid results in the `/grid` folder located inside the current working directory. Particle results(`particle_1.vtu`, `particle_2.vtu`, ..., `particle_41.vtu`) are referenced in `particleTimeSerie.pvd`, which can be opened in ParaView: File - Open - `particleTimeSerie.pvd` The mesh can be loaded with File - Open - `eulerianGrid.vtu`

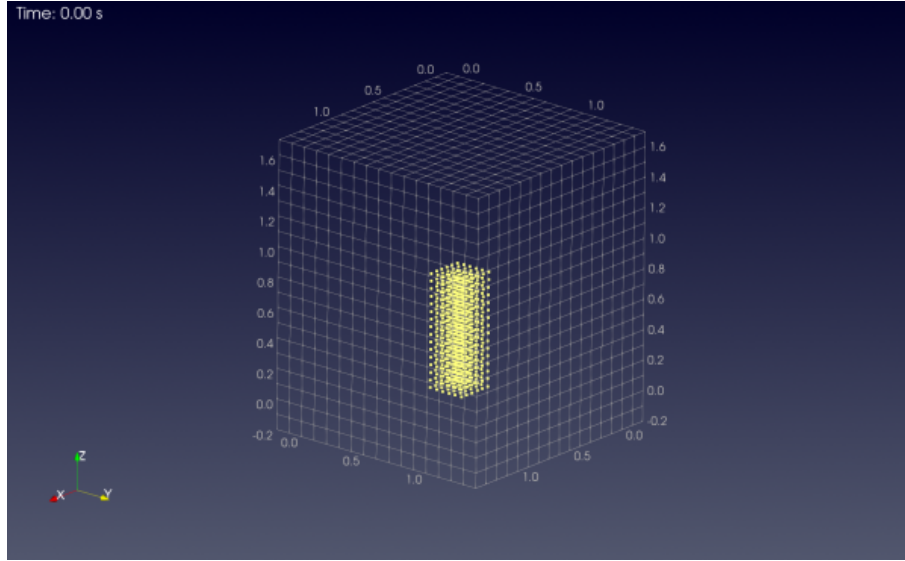


Figure 6: Particles and mesh of the analyzed case.

## Verification of Dynamic Boundary Condition

The velocity from the analytical input function

$$\dot{u} = A \sin(2\pi ft + \alpha)$$

was compared with the particle velocity at the base of the model. The results show excellent agreement between analytical and MPM-calculated velocities.

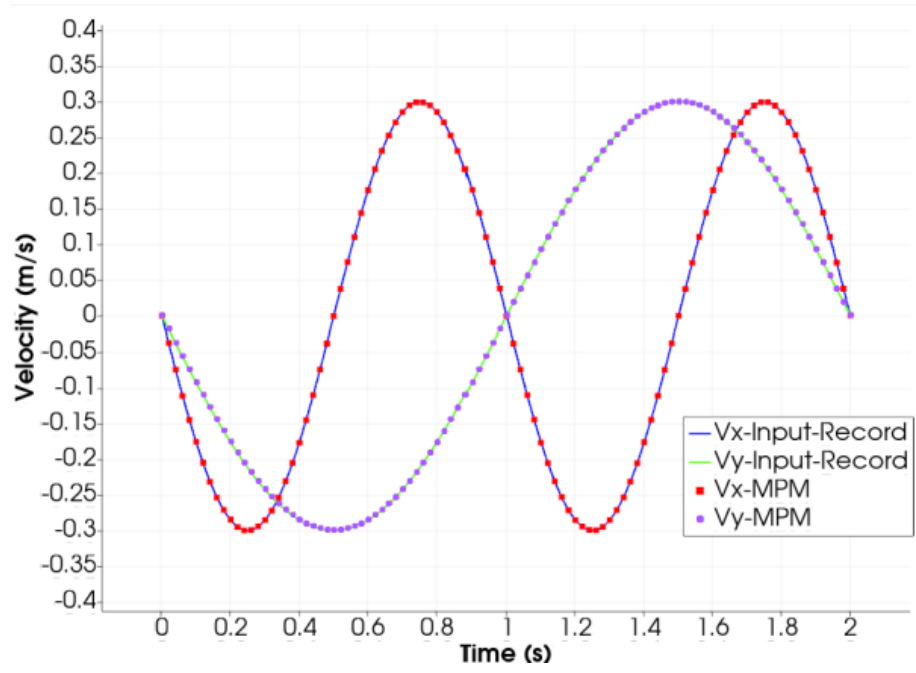


Figure 7: Verification of velocities obtained with MPM simulation.