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The construction process with the material point method

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ABSTRACT: The material point method has become a powerful tool in the geomechanical modelling of large deformation problems and it has been successfully applied in a large number of single and multiphase geotechnical problems involving excavations, changes in mechanical and hydraulic boundary conditions, as well as structure interaction. This paper presents the implementation of the construction process in a material point-based open-source code (Anura3D). The construction process is solved by activating the material points located in the volume under construction and gradually increasing the gravity assigned to those material points during the construction stage. The deformation of layers during construction, which, in practice, is compensated in the field to ensure the designed geometry, but generally neglected in modelling with the standard finite element method, is addressed in the implementation proposed. With this purpose, the method includes the option of filling with added material points the grid elements that become empty during the construction stage. The procedure is applied to the construction of an oedometric column build with a highly deformable elastic material. The effect of the number of layers is discussed and compared with the analytical solution.

Keywords: material point method; construction process; embankment; layer, oedometric column, fills

1 INTRODUCTION

The use of the material point method in engineering has increased in the last decades (Więckowski, 2004). Although with limitations and errors (González-Acosta, 2020; Berzins, 2022), the method is advantageous, especially for the analysis of large deformation of history-dependent materials. The method overcomes the limitations of dealing with large displacement and large deformation of the widely used standard finite element method (FEM).

Recent developments and applications of MPM demonstrate the capability of the method to simulate geotechnical problems including the entire process from the stable state (equilibrium) to failure triggering and large deformation post-failure behaviour. Fern *et al.* (2019) presented the MPM fundamentals and its application to the geotechnical engineering field. In the field of landslides, a large number of contributions can be found focusing on landslide propagation of one-phase materials (Yerro et al., 2016; Conte et al,, 2019), granular soils (Solowski and Sloan, 2014), saturated (Bandara and Soga, 2015) and unsaturated soils (Yerro et al., 2015), including liquefaction (Cuomo et al., 2019; Di Carluccio et al., 2023) and thermal interaction (Pinyol et al., 2018), as well as the interaction with structures (Mast et al., 2014; Ceccato et al., 2018). The triggering of failure is simulated by loading (Xie et al., 2023), changes in hydraulic boundary conditions as an increment of pore pressure (Alonso et al., 2014), loss of suction in unsaturated soils (Bandara et al., 2016), changes of external water level (Ceccato et al., 2021), dynamic actions in case of co-seismic landslides (Alsardi et al. 2021a, 2021b; Kohler et al., 2022), and excavation (Wang et al., 2016; Pinyol and Di Carluccio, 2019).

In the pioneer paper of Zabala and Alonso (2011), a dynamic coupled hydro-mechanical formulation adapted to MPM was developed and applied to evaluate the progressive failure of a dam foundation. The simulated processes included the dam construction by layers, although the paper focuses on the load applied to the foundation and the evolution of the failure. To the best of the author´s knowledge, there are no more contributions in MPM simulating the construction stages of earth fills, widely used in road, train, tailings, or dam embankments, which, on the contrary, had received a wide attention in FEM modelling. Earth structures are built by accumulating compacted layers, whose actual thickness is selected depending on the type of filling material~~,~~ and compaction procedure. In general, the thickness of the compacted layers ranges from a few centimetres, for fine granular materials, to more than 1 m, in the case of rockfill. When modelling the construction sequence numerically, it is not practical to simulate the relatively small thickness of the layers because it will involve a too-fine discretization of the domain, a high number of elements, and, therefore, a high computational cost. Consequently, thick finite layers (a few meters) are used in practice, which may have an important effect on the results, especially in the correct interpretation of the computed displacements. Naylor (1991) evaluated the construction stage FE modelling of different types of layered fills. The effect of the thickness of the simulated layers was analysed by (a) a one-dimensional model (restricted lateral strain) that could be accepted as a good representation of the central part of the layered embankments, and (b) a two-dimensional analysis to evaluate the influence of bending in "thick" numerical layers.

More recent examples on this topic can be found (Potts and Zdravkovic, 2001; Chen et al., 2014; Badarinath and El Naggar, 2021) that discuss the effect of the number of layers in the embankment construction simulation. Examples of modelling layered construction of real cases in which numerical results are compared with in situ measurements are provided by Naylor et al. (1986), Alonso et al. (2005), Rashidi and Haeri (2017).

This paper presents the simulation of the construction process in MPM. The code used is the Anura3D, an open-source code (Anura3D MPM Research Community, 2022). The input data for Anura3D calculations, in terms of geometry, initial and boundary conditions, and calculation specifications, as well as the plotting of results, are generated with the pre- and post-processing programs GiD (GiD, 2020). A general description of the code is first presented. Then, the construction process developed and implemented is described and evaluated for the simple case of a highly deformable soil column under oedometric conditions.

2 BASIS OF THE MPM AND ANURA3D

The material point method is a hybrid approach between the so-called particle method (Lagrangian approach) and the Eulerian-based method, as in the case of the standard finite element method. In MPM, the material domain is discretized by material points (MP) that carry all the information about material properties, constitutive parameters, and history variables. A stationary Eulerian grid, used to solve the equilibrium equations, discretizes the problem domain. The material points move freely through the Eulerian grid. This double discretization of the domain allows the modelling of large deformations without distortion of the computational mesh.

During the calculation step (Figure 1), all the information stored in material points, like mass, velocity, and initial momentum, are transferred to the mesh nodes (Step 1, Figure 1). During the Lagrangian phase, the governing equations of momentum balance are solved at the nodes, and the nodal accelerations are computed (Step 2, Figure1). In the Eulerian/convective phase, the material points velocities and momentum are calculated from nodal acceleration (Step 3, Figure 1). Nodal velocities are then computed from nodal momentum and, subsequently, the strain increments of material points. Mass balance equations and constitutive law are applied at the level of materials points and stress and pressure increments are updated, as well as the state variables (Step 4, Figure 1). The displacement and position of each material point are finally updated, the nodal mesh data discarded, and the computational grid is initialized (Step 5, Figure 1).

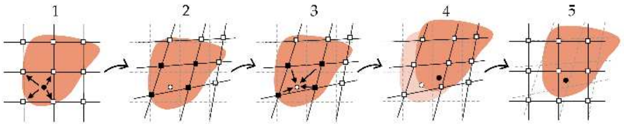


Figure 1. MPM computational cycle (Di Carluccio, 2021).

In this work, the one-phase approach (dry-condition) integrated explicitly is used to simulate the construction process implemented. However, the procedure can be used for implicit and multi-phase formulations (saturated and unsaturated conditions).

3 LAYERED CONSTRUCTION PROCESS

3.1 General aspects

Measured settlements in earth embankments during construction follow a parabolic curve with maximum displacements in the central part. Figure 2 shows, as an example, the settlements measured along vertical profiles located at the central axis of Albagès dam (Spain). Zero displacements are prescribed at the bottom of the embankment because the foundation settlements, relatively small, are not included. At the top, settlements are zero because the dam height, imposed during construction according to the design, and the settlements occurring in the top layer are compensated during construction. The observed displacements mainly result from the integration, along the embankment height of the vertical strains induced by the weight of the fill materials accumulating during construction. However, other factors like compaction conditions (magnitude and type of the compaction loading, water content and target density), as well as atmospheric conditions, may become relevant.

Simplifying to an oedometric column, a good approximation for the central part of the embankments, and for the simple assumption of an elastic material, characterized by a Young modulus (E) and a Poisson ratio (ν), the settlement, δ_v, at a height h (for a total embankment height H), can be calculated as

$$\delta_v = \frac{(1-2\nu)(1+\nu)}{E(1-\nu)} h(H-h)\gamma \qquad (1)$$

where γ is the specific weight of the material. This equation corresponds to a parabolic curve.

The numerical modelling of the construction by finite layers thicker than used in practice affects the computed settlements, even under elastic and oedometric conditions, as discussed below

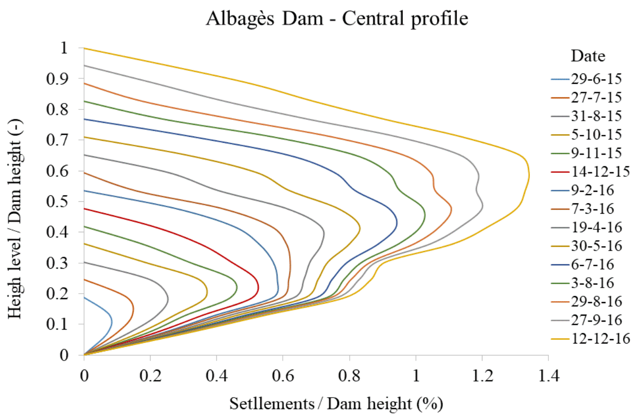


Figure 2. Measured settlements in the central profile of Albagès dam (from Pinyol and Alonso, 2019).

Under these simplified assumptions, the vertical stresses are equal to the overburden load because of vertical equilibrium, whereas the horizontal stresses are determined by the value of K_0 or Poisson ratio defined as an input parameter (Potts and Zdravkovic, 2001).

Since the compaction procedure is not explicitly simulated, conditions reached during compaction should be included as initial properties. In the case of simplified modelling, initial conditions are the initial stiffness and porosity. More complex constitutive models may be able to include the initial compaction condition in terms of state variables that are directly related to the compacted variables actually controlled in practice: water content and dry density (Alonso and Pinyol, 2008). As an example, the effect of the compaction conditions (water content and dry density reached) explains the shape of the curves measured in Albagès Dam (Figure 2), which shows larger settlements in the lower part of the dam (Pinyol and Alonso, 2019) because of a higher compaction water content if compared with the rest of the dam. More advanced models are also capable of including the effect of the microstructure developed during compaction, as discussed in Alonso et al. (2013).

3.2 Construction process in MPM

The construction procedure has been implemented in MPM Anura3D code for 2 and 3 dimensions. The examples presented here were carried out in 2 dimensions.

The procedure consists in simulating the construction of previously defined finite-thick layers. First, in the pre-processing stage, the geometry of the model to be constructed should be defined, distinguishing the construction volumes (layers). Material properties, initial state variables and initial conditions, should be defined. The construction of each layer will be simulated during the calculation steps indicated by the user. When a material volume is constructed, the initially defined material points per element filling the grid elements of the volume in construction are activated. No stresses are assigned initially to those material points. Only the density, volume, initial state variables, and initial conditions are assigned. The weight of the materials points in construction will increase gradually by increasing the gravity during the time allocated to the construction stage. This procedure is generally employed in the finite element method (Potts and Zdravkovic, 2001; Alonso et al., 2005).

The deformation of a volume/layer during construction may involve a significant change of geometry that in practice is compensated during construction because new material is added and compacted to match the designed geometry. This effect, generally neglected in standard finite element simulations, can be considered in the MPM modelling implemented.

To simulate the addition of material to compensate for the movements occurring during construction, it is possible to fill the elements of the computational mesh covering the domain that corresponds to the built volume/layer, which becomes empty (due to displacements) during its construction stage.

In the current implementation, the refilling option can be activated or deactivated by the user.

If deactivated, it could be of interest in case of failure of the structure under construction. In this case, it is convenient to simulate the failure without refilling elements that become empty during the large-displacement motion.

The implemented construction process in Anura3D follows the steps indicated below. As an example, the construction is referred to the simple example represented in Figure 3:

Pre-process

1. The entire material domain, soil properties, initial and boundary conditions should be specified. In the example (Figure 3), an oedometric column, the calculation domain and its characteristics should be defined (the three layers) at the beginning.
2. Elements to be constructed at the same stage should be grouped into layers. The construction period (initial and final calculation steps specified by the user) should be assigned to each construction layer. In the example, each layer is constructed at different stages.

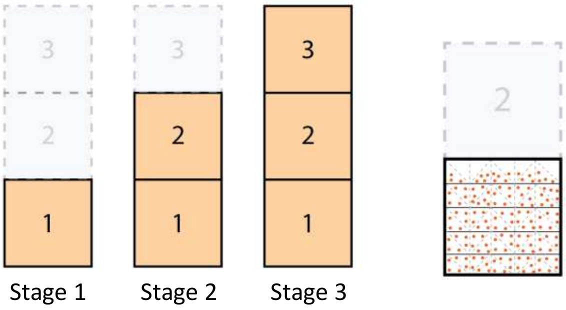
Construction stage and calculation phase

3. Materials points of the layers to be constructed in the current stage are activated and initialized with the properties of the assigned material, as well as the initial position, volume, density, element identification, material type, initial velocity, stress and state variables.

4. The gravity assigned to the materials points under construction increases gradually during the calculation steps of the construction stage.

Check of empty elements and refilling of material points

5. (Optional) During construction stage, once the material point positions have been updated, some elements of the volume under construction can become empty (Figure 3b, where three elements become empty). If activated, during the actual time step, these elements can be refilled with the same number of the initial material points and the same properties initially assigned to the volume. The initial value of gravity of those added material points is the same that the current gravity load applied at the moment of the refilling. This refill of elements continues till no further elements become empty during the time step.



(a) (b)

Figure 3. (a) Example of construction of a column in three stages; (b) Position of the initially activated material points during the calculation of layer-1 construction stage.

4 LAYERED CONSTRUCTION OF AN ELASTIC OEDOMETRIC COLUMN

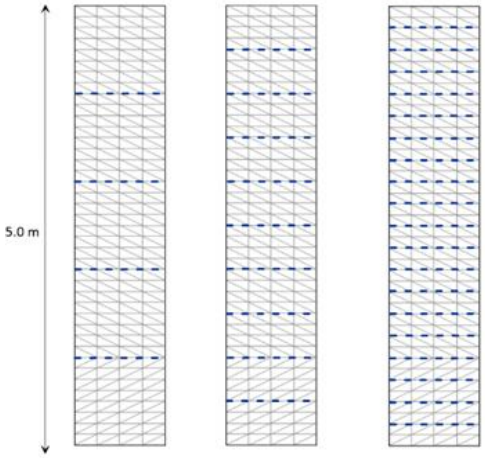
The implemented construction procedure is evaluated by modelling a soil column under oedometric conditions with different numbers of layers. The results are compared with the analytical solution (Eq. 1).

To accelerate the convergence to the equilibrium (quasi-static calculation), artificial damping is applied by imposing a damping force on nodes proportional to the magnitude of the unbalanced forces and in an opposite direction of their velocity. The damping factor used in the calculations is 0.75.

4.1 *Material properties, geometry, and mesh*

The total column height is 5.0 meters. The material is defined as linear elastic with a Young modulus of 400 kPa and a Poisson's ratio of 0.25. The initial density is 1720 kg/m^3 and the initial porosity is 0.35. Lateral boundaries are fixed in the horizontal direction. The bottom of the column is fixed in the vertical direction.

Three construction processes are simulated, using 5, 10, and 20 layers. During each stage, a layer of the column is built. The same mesh is defined in all the cases. It consists of a structured linear triangular mesh with elements 0.125 m high. Therefore, the construction process will involve 8, 4, or 2 element rows per layer depending on the number of layers (5, 10, or 20, respectively), as shown in Figure 4. Three material points are initially assigned per element located at Gauss point positions.



(a) (b) (c)

Figure 4. Geometry, mesh discretization of the soil column; a) 5 layers; b) 10 layers; c) 20 layers of construction.

4.2 *MPM results*

This work focuses mainly on the settlement and displacement evolution during construction.

Figure 5 shows the computed displacements of the column during the construction, using 5 layers. The results show the displacement computed in material points located near the central part of the column at the end of each construction stage. The vertical axes indicate the relative initial height of the materials points selected. The abrupt jump observed between layers is because when a new layer is built, the accumulated displacements of the new material points are nil, whereas materials points previously built accumulate settlements. The maximum accumulated displacements occur at the layer located at the central part of the dam, as observed in real cases.

Figure 6 shows the vertical displacement profile at the end of construction for the different number of layers, compared with the analytical solution (Eq. 1). Two values of density have been considered: the initial one (1720 kg/m^3) and an average density value calculated in MPM after column deformation for the case of 5 layers (1870 kg/m^3). The difference observed depends on the numbers of layers as well as on the overburden stress that depends on the computed density. Results in Figure 6 consider the refilled of empty elements after each step.

The effect of filling the elements that become empty during calculation is highlighted in Figure 7. The final displacement in the case of filling the empty elements is limited by the thickness of the mesh elements. The maximum settlement becomes larger in the case of non-filling of the elements.

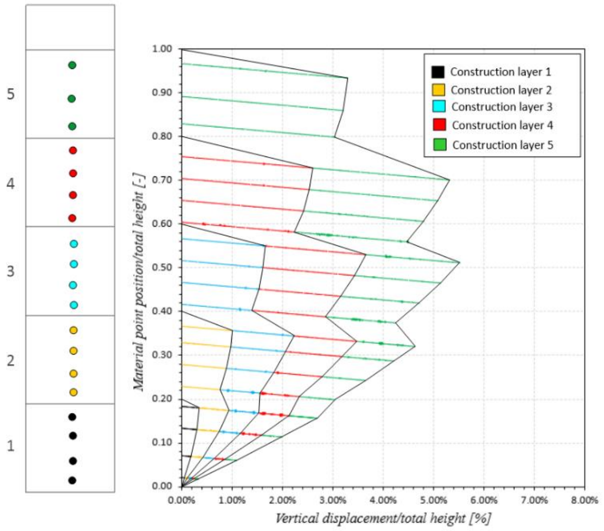


Figure 5. Computed settlements during the construction of the column. Five layers.

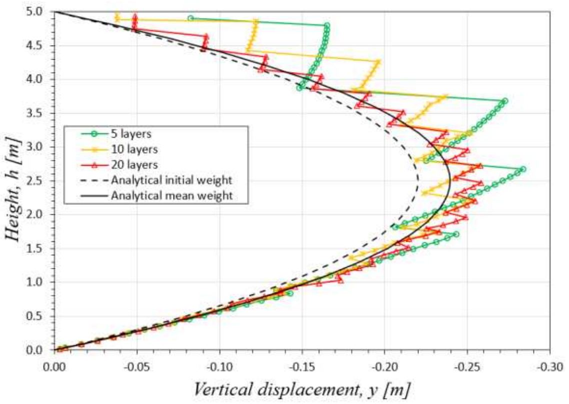
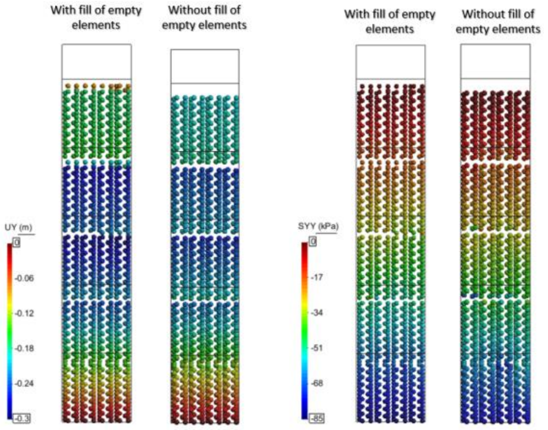


Figure 6. Effect of the number of layers in the vertical displacement.



(a) (b)

Figure 7. a) vertical displacements and b) vertical stresses at the end of construction (5 layers).

This unexpected result is explained because when empty elements are not refilled, material points added above during the next construction stage move freely to the space left by empty elements. On the contrary, when elements are refilled, the overburden stress increases but the settlement depends on the already-built soil stiffness. The increment of the weight in the case of element refill is observed in terms of vertical stress in Figure 7b. Maximum vertical stress is lower (77 kPa) when elements are not filled, and it increases to 83 kPa due to the added particles. This additional stress is produced by the extra weight of the additional material points used during the construction of the layers.

The construction of the column was also simulated with finite element software Code_Bright (Olivella et al., 1996; Olivella et al., 2019), as shown in Figure 8.

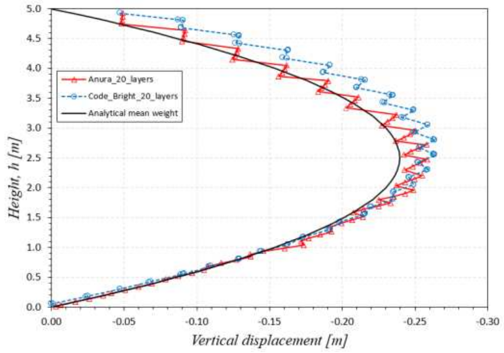


Figure 8. Vertical displacements of the soil column using 20 layers, results from FEM (Code_Brigth) and MPM.

The calculated displacement profiles are similar in both cases, FEM or MPM (Figure 8). Then, the construction process can be adequately simulated using MPM with the advantage of allowing large displacements of the material without the difficulties of the mesh distortion during the construction or in the case of instability.

5 CONCLUSIONS

The construction process of embankments is described and simulated using the material point method. The examples provided in this paper include only elastic materials. The use could be extended to other constitutive models. The implementation offers the possibility of filling the grid elements that become empty during construction by adding new numerical particles. This option simulates the actual construction process of embankments and addresses the "compensation" of settlements adopted in practice to reproduce the design geometry. The procedure provides a more accurate prediction of settlements and stresses.

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