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Material Point Method for Modeling the Static Liquefaction-Induced Fundão Dam Failure

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Abstract

The Material Point Method (MPM) is recently considered a powerful tool in analyzing slope failures because of its capability to model the progressive failure of slopes as well as handling problems that involves large deformations. In this study the failure of Fundão Dam, which took place in November 2015 in Brazil, induced by static liquefaction is analyzed using the MPM. The MPM code Anura-3D is used to predict the dam slope progressive failure and to simulate the large deformations produced post failure. The failure wedge obtained from MPM analysis of this study is compared with the failure surfaces obtained from the Limit Equilibrium Analysis (LEA) provided by two independent studies carried out on Fundão Dam slope. The failure wedge obtained from the MPM show good agreement to the pre-defined failure surfaces obtained from LEA. However, the MPM has a great advantage over the LEA in simulating the mode of failure and in modeling the large deformations that took place upon failure. The only drawback of the MPM approach is that it does not provide a value for safety factor against failure; however the new approach is still under-developed and could be easily enhanced to provide a unified analysis tool for slope stability problems.

Keywords: Fundão Tailings Dam, Static Liquefaction, Material Point Method, Large Deformations.

Introduction

The 110 m tall Fundão Tailings Dam, located in the south-eastern Brazilian State of Minas Gerais, collapsed on the 5th of November 2015 in a liquefaction flow slide that was initiated at the dam's left abutment. The Fundão Dam was mainly constructed to retain sand and slimes deposits that were produced from an iron mineral extraction process**.** The failure released approximately 43 million cubic meters of iron mineral tailings, causing major environmental problems as polluting

668 km of water courses from the Doce River to the Atlantic Ocean, and it sadly resulted in 19 deaths [1, 2].

Following the collapse, a report was carried out by the Fundão Tailings Dam Review Panel, Morgenstern et al [2] to investigate the reasons behind the dam failure and it was published on the 25th of August 2016. The panel investigation was based on the interpretation of cone penetration tests (CPTu) carried out at the dam site, laboratory testing of deformation-induced stress paths, and numerical modeling [2].

The report concluded that the conditions necessary for static liquefaction to occur within the Dam were present prior to failure. The static liquefaction is a destructive process in which loose saturated granular material loses its effective stress causing vast deformations in response to an applied static stress. In this case, the presence of the loose saturated sand tailings (a mixture of sand and silt particles), the ineffectiveness of the proposed draining system within the dam, and the lateral extrusion of slimes tailings (fine low plasticity clay-like layer) behind the sand, provided the mechanism to trigger the static liquefaction and consequently the dam failure.

The original design concept of the Fundão Dam included the presence of an unsaturated compacted sand zone to retain the slime tailings. The design was initially destined to maintain adequate drainage system within the sand layer by the presence of a dike at the starter dam underlain by a high-capacity base drain of gravel and rock, so that the sand layer remains unsaturated and not susceptible to liquefaction. However, depositing the sand tailings by hydraulic means resulted in its loose un-compacted condition. In addition to that, different mistakes that took place within the construction of the high-capacity drainage system resulted in failure in its mechanism [2,3]. Both factors lead to the formation of the saturated loose sand layer that is vulnerable to liquefaction.

Although the sand tailings at both abutments were generally loose, static liquefaction only occurred at the left abutment. At the right abutment, the efficiency of the high-capacity drainage system at the base of the starter dam was the reason for its subsistence. The water was allowed to drain from the sands and lower its saturation. On the other hand, all the necessary conditions for static liquefaction to occur at the left side were present. The more compressible slimes that had intruded the sand beach area with its low permeability impeded the free flow of water. As a result, the free-drainage path required to control the phreatic surface was inhibited which enhanced saturation and induced undrained shearing of the tailings, Morgenstern [2]. In addition to that, and unlike the right abutment, the deposition of slimes in areas where this was not intended at the crest alignment setback at the left abutment caused a lateral extrusion mechanism to develop [2].

Figure 1 presents a generalized scheme of the Fundão dam's left abutment showing the sand and slimes tailings retained by the dam and supported on bedrock foundation. The figure also shows the intrusion of slimes into areas originally reserved for sands and which was consequently the main cause of the flow failure that took place.

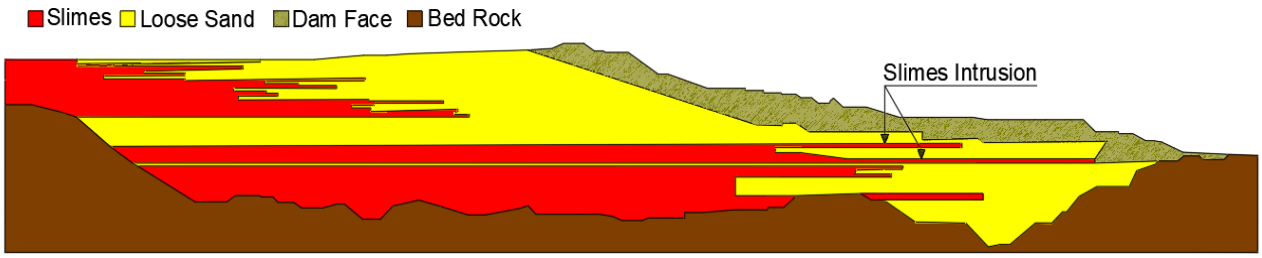

Fig. 1 Generalized Scheme of the Fundão Dam Left's Abutment Showing the Intrusion of Slimes into Areas Originally Reserved for Sands, Modified after [5]

Four years later, Reid D. [4] carried out a detailed study to investigate the reasons behind the dam failure. In that paper, the available CPTu data were digitized to enable a more comprehensive use of the data and to assess which methods likely were used to interpret the state. As a result, a zone of looser sandy tailings at the location where liquefaction was likely to have triggered was identified. Examination of historical data indicated a potential source for this loose material. Another recent research was carried out by Sadrekarimi, A. et al [5] where they analyzed the failure of Fundão dam using an iterative limit equilibrium method to obtain the factors of safety (FS) for liquefaction triggering and flow failure. The study presented a comprehensive static liquefaction triggering analysis performed on the failing section of the dam prior to its collapse. The FS and the slip surface for liquefaction flow failure were evaluated based on the limit equilibrium analysis proposed by Sadrekarimi, A. [6] and the failing dam's section was found to be susceptible to static liquefaction failure with a factor of safety of 0.56 while the recommended cut-off value for the safety factor is 1.5.

Material Point Method

There are different approaches that deal with slope stability geotechnical engineering problems either for practical situations or research purposes. In traditional slope stability analysis, the Limit Equilibrium Method (LEM) is one of the most common approaches for estimating the factor of safety against slope failure and in identifying a failure surface/line. SLOPE/W is one of the most common software using limit equilibrium based slope stability analysis modules. However, this simple method cannot provide information on the soil deformation and is not simulating the real soil failure wedge. Other well-established method is the Finite Element Method (FEM) which can model complex geometries and soil behaviors. However, FEM is limited to small deformation analyses and cannot model post-failure behaviors [7]. New numerical methods are being developed in order to provide a tool capable of simulating the progressive failure process of any slope as well as identifying a failure wedge close to reality such as the Material Point Method (MPM).

MPM has been recently applied to a number of different geotechnical problems but mainly to the ones involving large deformations and progressive failure such as landslides and slope/dam

failures. In addition, based on its capability to model dynamical conditions, it has been used in the determination of stress and deformation in the vicinity of blasting slope failures [8]. Its use has been also extended to solve flow-deformation problems in saturated conditions as it can simultaneously model fluid-like and solid-like behaviors [8].

MPM is considered a new approach used for analyzing slope failures, which is the concern of this study, yet the approach is still under developed. The main drawback in MPM analysis when used for slope stability analysis problems is that the slope factor of safety, which is commonly of great concern to designers, cannot be obtained directly from the MPM. To address this issue, a new chart method for a FS evaluation incorporated with MPM has been recently proposed by Zhang et al. [9]. The strength reduction method (SRM) is combined with MPM to evaluate the Factor of safety and thus enhance the use of MPM in many slope stability analysis problems [9].

Briefly, the MPM could be defined as an Eularian-Lagrangian method. It describes the deformation of a continuum body that can be continually sub-divided into infinite small elements with same properties of the bulk material. The deformation of the continuum body is discretized by a finite number of Lagrangian material points moving through an Eulerian background grid. It moves these points in a computational grid by solving Newton's governing equations. MPM does not suffer from mesh distortion and it has the advantage of being able to solve the governing equations for the different phases with distinct layers of MPs [10, 11].

Figure 2 shows the basic MPM computational procedure and the steps could be summarized as follows [12]:

(1) In the start of the computational procedure, the information carried by material points (velocity, mass, volume) is projected to the nodes of the background mesh.

(2) Equilibrium equations are solved onto the nodes, resulting in updated nodal velocities and positions.

(3) The acceleration and velocity fields obtained at the background nodes are mapped to material points, and are used to calculate strain and strain rate at the material points to update stress and history variables using a continuum constitutive model.

(4) Finally, the positions of the material points are updated, and the computational mesh is reset.

MPM has been progressively used for slope stability analysis problems in recent years [7, 9, and 12]. In this study, MPM is used to simulate the slope failure and the large deformations that occurred within the continuum solid mechanics framework of the liquefaction–induced Fundão dam failure that took place in November 2015.

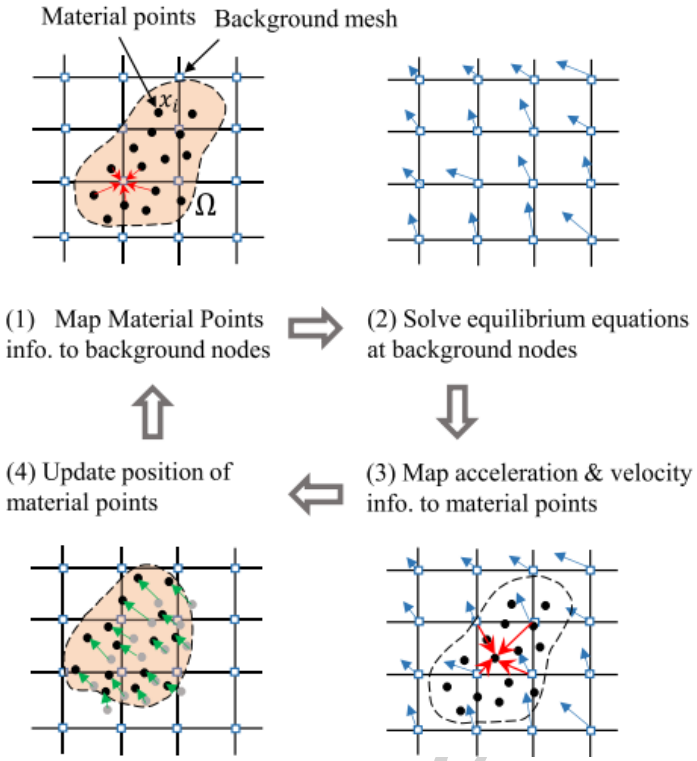

Fig. 2 Computational Framework of Material Point Method, after Soga et al. [12]

Fundão Dam Characterization (Geometry and Geotechnical Properties)

The dam's slope geometry, geotechnical characterization, and advanced testing data used in this research are obtained from the Fundão Tailings Dam Review Panel report by Morgenstern [2]. Figure 3 shows a simplified cross section of Fundão dam's left abutment created and embedded in the MPM analysis of this study. The figure shows the slope geometry, the materials stratigraphy, and phreatic surface. The stability analysis is carried out at dam model geometry right before the failure in November 2015. The dam crest elevation at this section was 901 m and the downstream elevation was 845 m with a total slope height of 56 m. The overall downstream slope was 6.2H: 1V as illustrated in Figure 3. The model materials layering that is composed of loose sands, slimes tailings, and bedrock are also shown in the Figure.

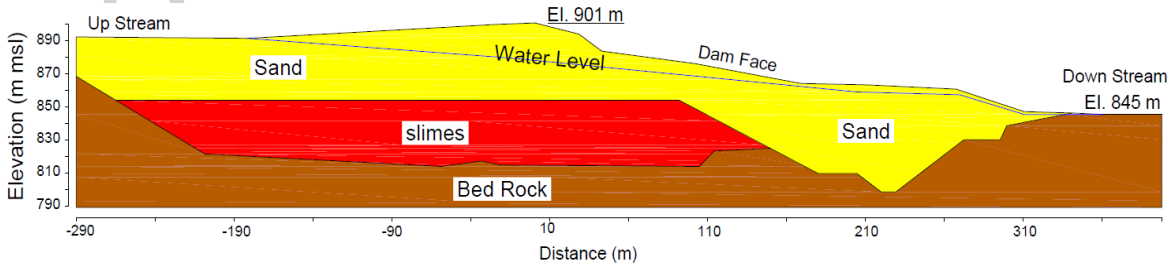

Fig. 3 Cross Section of Fundão Dam's Left Abutment Used in the MPM Analysis of this Study

Table 1 shows the Fundão Dam Tailings and Rock Properties used in the MPM Analysis of this study. A unified total unit weight of 22 kN/m^3 was assigned for all materials based upon the results of the field and laboratory investigations conducted by the Panel and given in Morgenstern report [2]. The critical state of the angle of internal fiction of the sands and slimes tailings were determined from Triaxial compression tests, also carried out and given by the panel in the Morgenstern report [2].

Table 1 Fundão Dam Tailings and Rock Properties used in the MPM Analysis of this Study Based on the Findings of the Expert Panel Report [2]

Dam Tailings and Rock Properties	Layer Name	Layer Description	Specific Gravity, Gs	Effective unit weight, γ' (kN/m^3)	Cohesion, C (KPa)	Angle of internal friction (ϕ'_{cs})
Layer 1	Loose Sand Tailings	Cohesionlesssilty Sand (SM) with non-plastic fines content of 40%	2.85	22	----	33
Layer 2	Slime Tailings	Low plastic silt and clay (CL-ML) with an average fines content of 20%	3.95	22	----	28
Layer 3	Bedrock	Weathered metamorphic rock (Phyllite Rock)	2.73	22	40	32

MPM Anura-3D Code and Steps of Processing

The material point method code used in this study is released by Anura3D research community in 2021 [13]. The whole analysis process consists of three phases: 1) the pre-processing phase; 2) the calculation phase; and 3) viewing the results.

The First phase is done by GID software [13]. In this phase, the basic steps such as drawing the model geometry, assigning the material properties, as well as determining the fixities and determining the number of material points and number of calculation phases were carried out.

The final step generates a file ready for calculation phase. For the calculation phase, we use the visual studio program to compile the Anura3d MPM code and then use it to run the files generated from the phase No. (1).

In phase No. (3), viewing the results, PARA-VIEW software [13] is used to visualize the stresses, strains, displacement of solids, and the deformation shapes. Figure 4 presents the three phases used in the MPM numerical modeling analysis showing the software used in each phase.

Fig. 4 Steps of Performing a Numerical Modeling Presenting the Pre-and Post-Processing Phases with Anura3D

MPM Fundão Dam Analysis

Fundão Dam modeling starts by the pre-processing phase using GID. The downstream boundary is located 200 m from the toe of the starter dam, while the upstream boundary is located at the rear of the dam. The model is divided into three layers: sand, slimes, and bedrock, and it is represented by a mesh with 1110 triangular elements. All materials in the model are modelled as saturated material - fully coupled and the Mohr-Coulomb constitutive law is assigned for all material types. Material points assigned for the model are 2D-single point formulation with 6 nodes per the element. Table 2 summarizes the model basic Properties and material properties as used in MPM Fundão Dam Analysis.

Fundão dam comprises two-phase analysis; the first one is generating the initial stresses while the second one is applying the triggering lateral load. The boundary conditions are defined as follows: Left side: horizontal fixity in x-direction; Right side: horizontal fixity in x-direction; Top side: vertical fixity in y-direction; Bottom side: full fixities in x- and y-direction. In this study, the water level is considered at the ground surface of the dam as a worst case scenario. A lateral pressure of 150 kPa is applied at the rear of the dam representing the lateral force imposed from the slimes extrusion as the trigger of the failure.

Table 2 MPM Model Basic Properties and Material Properties Solids Based on the Findings of [1,2,5]

Basic Properties	***Loose sand***	***Slimes***	***Bed rock***
Initial porosity	0.45	0.51	0.4
Density Solid (kg/m^3)	2850	3950	2730
Density Liquid (kg/m^3)	1000	1000	1000
Intrinsic Permeability (cm/s)	3 E-4	1.0 E -6	1.2 E -7
Material Properties Solid			
Material model Solid	Mohr-Coulomb		
Effective Poisson Ratio	0.3	0.2	0.2
Effective Young Modulus (kPa)	8000	9500	408000

Effective Friction Angle (°)	33	28	32
Effective Cohesion (kPa)	0.0	0.0	40
Effective Dilatancy Angle (°)	0.0	0.0	0.0

Figure 5, 6, and 7 show the material types and the background mesh, the model boundary conditions, and the lateral pressure assigned at the dam rear to simulate the lateral extrusion that triggered the static liquefaction and consequently the dam failure respectively.

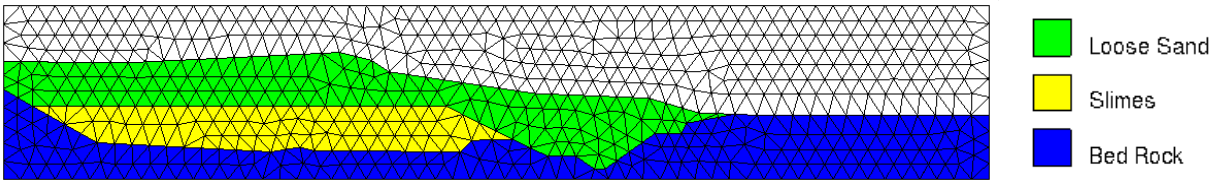

Fig. 5 Material Types and the Background Mesh

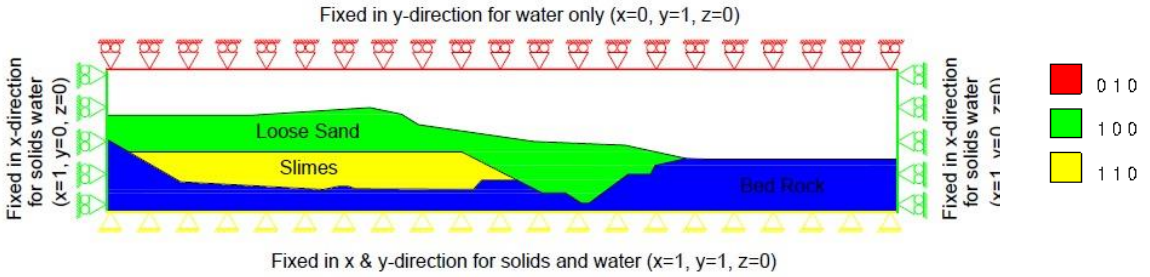

Fig. 6 Boundary Conditions of the MPM Model

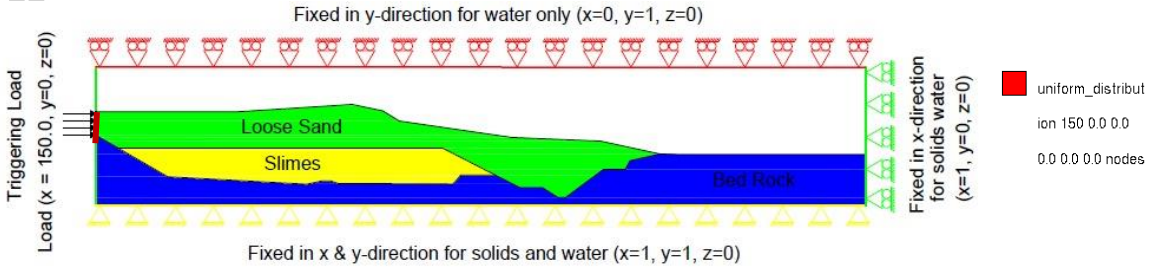

Fig. 7 Lateral Pressure at the Rear of the Dam Representing the Trigger of the Failure

Results and Discussion

Generally, there is uncertainty in the calculation of the factor of safety for the existing tailings dam due to the lack of understanding the material behavior of the tailings since it is a hematite-based soil not silica based soil. Therefore, the regular safety audits for the tailings dam will not produce a realistic status for such dams. Hence, failure control techniques should be done at the down-stream direction, the failure direction, to ensure the safety measure for the people and the environment from such toxic flow failures. Failure control techniques in the down-stream side will be in the form of barriers or any similar structures. These protection structures should be designed according to the failure mechanism, failure runoff length, wedge failure thickness, and failure mass velocity. Such failure actions cannot be provided by the conventional analysis approaches such as: Finite Element Method (FEM), Finite Difference Method (FDM), and Limit Equilibrium Analysis (LEA). Meanwhile, MPM emerges as powerful tool that can predict these failure actions and helps in containing any post failure features. Consequently, MPM can be used in the type of problems that include large deformation analysis. However, it suffers from some limitations to be able to used it solely as it cannot calculate the factor of safety against failure if compared to the methods mentioned earlier and this due to the very recent formulation of the MPM codes [13].

The evolution of the Dam failure over time as obtained from MPM Model analysis is shown in Figure 8. The figure presents the progressive failure mechanism of the Fundão Dam which is a powerful feature obtained from MPM analysis to simulate the entire process of slope failure, the final runoff length and the slope large deformations. The simulation of such complicated post-failure behaviors such as runoff and deposition of landslide masses, are easily captured in MPM analysis, while it is very difficult to obtain using any conventional numerical method tools.

Another significant result of the MPM analysis is an accurate prediction of the geometry of the slope failure. To illustrate this result, the MPM model result was compared with the results obtained from the Limit Equilibrium Analysis (LEA) provided by Morgenstern [2] and Sadrekarimi, A. [5].

Figure 9 shows the comparison of the wedge failure obtained from MPM model to the failure surfaces obtained from the LEA carried out by two independent studies [2,3]. It is shown that there is a good agreement between the MPM results and those obtained by the LEA. However, it should be noted that the in the LEA of both Morgenstern [2] and Sadrekarimi, A. [5], the failure surfaces were pre-defined and its beginning and end were controlled. On the other hand, using MPM code, the failure surface was not specified in the analysis procedure. It is also noticed that the beginning of the failure line is very sharp while the failure wedge obtained from MPM is more realistic and predicts a complete wedge failure not a failure line.

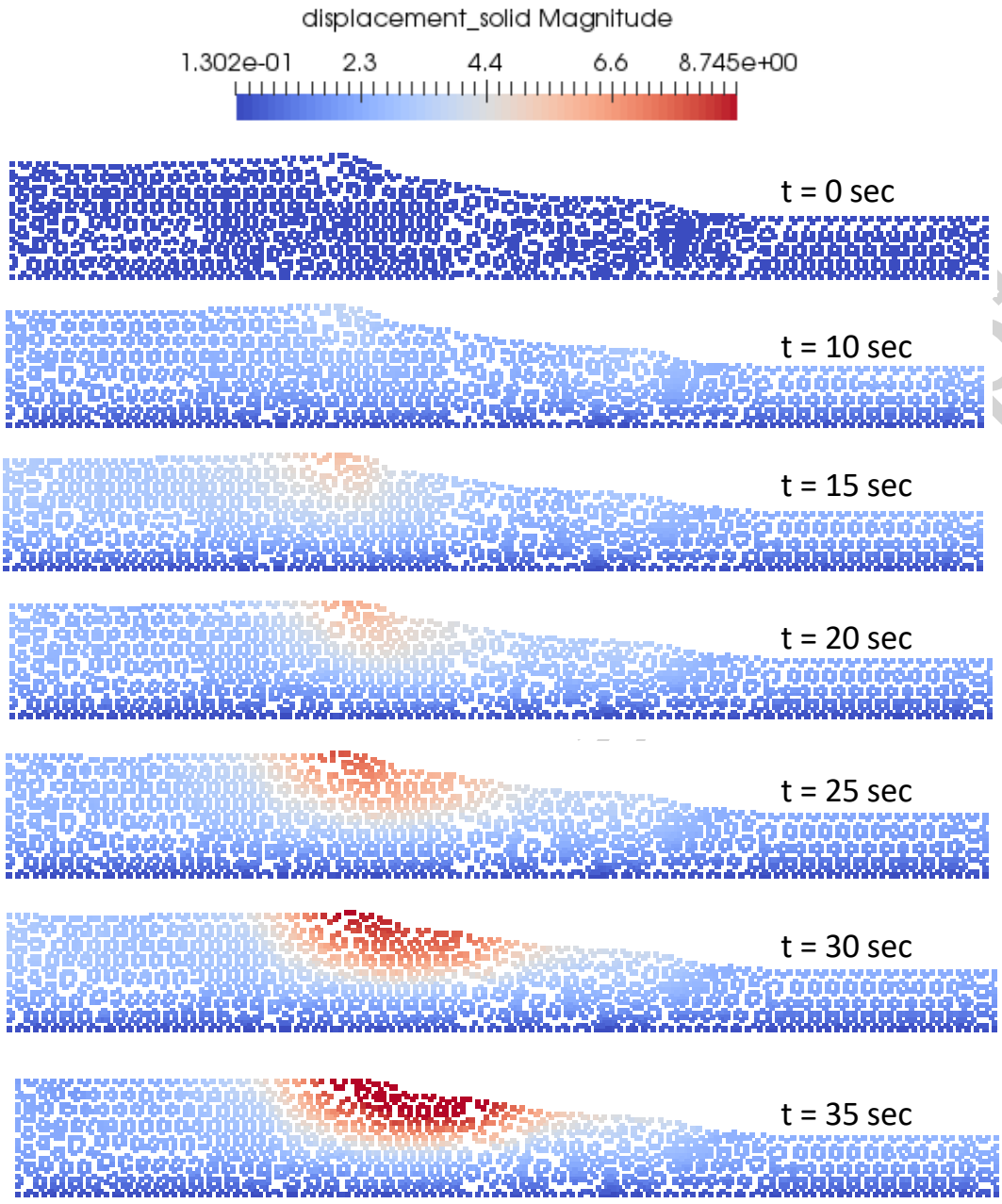

Fig.8 The Evolution of the Fundão Dam Failure Over Time Obtained from MPM Model Analysis, solid_displacment,m

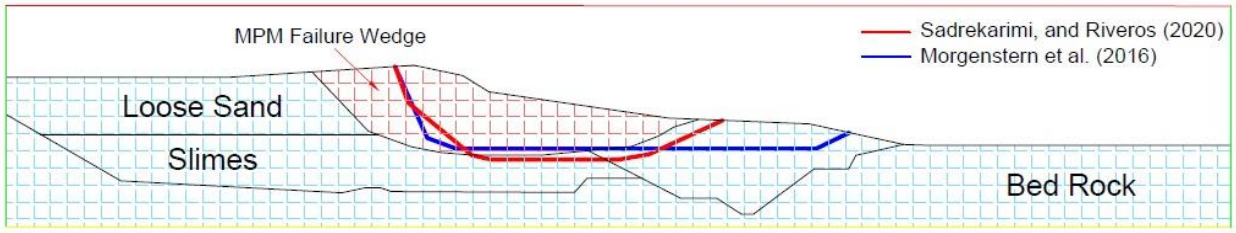

Fig. 9 Comparison of the Wedge Failure Obtained from MPM Model of this Study with the Failure Surfaces Obtained from LEA Carried out by Two Independent Studies [2, and 5]

Conclusions

In this study, MPM is used to simulate the liquefaction-induced failure of Fundão dam's left abutment that took place in November 2015. The MPM proves to be a very good and unique tool in modeling the progressive failure mechanism of soil slopes over time and in identifying the large deformations accompanied by the dam failure. Failure features such as the dam crest loss thickness and the final slope failure runoff length were captured using MPM. Compared to the traditional slope stability analysis methods (such as FEM, FDM, and LEA), the MPM gives a better depiction of failure and hence can help in containing post-failure actions. The disadvantage in using MPM is that it is not a user-friendly commercial software as it needs special codes to be downloaded and programmed. Also its main drawback is that the Factor of Safety (FS) against failure cannot be obtained directly using it which makes it inconvenient in practical slope stability analysis. Further research is needed to incorporate the FS evaluation with the slope failure large deformation analysis within a unified framework. Although the MPM is still an under-developed method, it is emerging as a powerful tool in different geotechnical engineering problems and thus it is gaining popularity with time.

Declarations

Conflict of interest: The authors declare that they have no conflict of interest.

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