USING THE MATERIAL POINT METHOD TO EXAMINE POST-EARTHQUAKE STABILITY OF SLOPES AND EMBANKMENT DAMS

Jack Montgomery PE, PhD[1]
John Murphy, PE[2]

ABSTRACT

Earthquake-related failure modes for embankment dams are commonly evaluated through numerical simulations using finite element or finite difference approaches. This is especially true for liquefaction triggering or cyclic softening of fine-grained materials where advanced constitutive models are used to capture the dynamic response of the dam and the nonlinear behavior of the soil. Both liquefaction and cyclic softening can lead to significant strength loss, which can lead to large deformations within the dam, but these numerical tools often cannot capture these large deformations due to excessive mesh distortion and subsequent numerical errors. This leads to significant uncertainties in estimating potential crest settlement, which is often a critical value for risk assessments of dams. Hybrid numerical methods like the material point method (MPM) offer a promising alternative to model large deformations, but their application to dams is still limited and relatively little validation has been done on using MPM for post-earthquake stability analyses. This study focuses on applying MPM simulations to evaluate the post-earthquake stability of a hypothetical embankment dam and to examine potential deformations of a flowslide that occurred in Palu, Indonesia in 2018. The MPM program Anura3D is used for the analyses with modifications to allow for assigning residual strengths. The results from the Palu flowslide are compared with observations from the field to show that the MPM analyses are able to capture the extent of the slide, but underpredict the measured displacements in the central portion of the flowslide. The analyses for the embankment dam are compared with post-earthquake stability results from finite difference analyses using FLAC. The MPM analyses are able to capture the full deformation of the flowslide, while the FLAC analyses are halted due to excessive mesh deformation. These results demonstrate the potential of MPM to be used as a complement to existing numerical tools for evaluating the seismic response of dams, but additional work is needed to validate this approach using case histories with both large and small deformations.

INTRODUCTION

Earthquake-related failure modes for embankment dams are commonly evaluated through numerical simulations using finite element or finite difference approaches. This is especially true for liquefaction triggering or cyclic softening of fine-grained materials where advanced constitutive models are used to capture the dynamic response of the dam and the nonlinear behavior of the soil. Both liquefaction and cyclic softening can lead to significant strength loss, which can lead to large deformations within the dam, but these

[1] Associate Professor, Auburn University, Auburn, AL, jmontgomery@auburn.edu
[2] Research Civil Engineer, US Army Engineer Research and Development Center, Vicksburg, MS, john.w.murphy@usace.army.mil

numerical tools often cannot capture these large deformations due to excessive mesh distortion and subsequent numerical errors. These leads to significant uncertainties in estimating potential crest settlement, which is often a critical value for risk assessments of dams. Hybrid numerical methods like the material point method (MPM) offer a promising alternative to model large deformations, but their application to dams is still limited and relatively little validation has been done on using MPM for post-earthquake stability analyses. The recent USSD Earthquakes Committee report on estimating earthquake-induced deformations of dams (USSD 2022) highlighted MPM as a potential new tool for performing these analyses, but additional work is needed to build confidence in the results. This presentation will demonstrate the use of MPM simulations to model the post-earthquake stability of dams affected by liquefaction.

METHODS AND ANALYSIS

MPM is a hybrid method that combines some features from particle-based methods and some from traditional finite element methods (FEM). The MPM uses movable material points to represent the continuum (i.e., the soil, rock, and water of an earth dam) and a fixed grid of finite elements to perform the computations. This process is illustrated in Figure 1. Some of the earliest applications of MPM to solid mechanics problems were presented by Sulsky et al. (1995), while more recent developments, including extensions to solve coupled hydro-mechanical problems, are discussed by Soga et al. (2016).

Advantages of MPM include the ability to model large deformations without mesh distortion, the ability to simulate coupled problems, and the use of advanced constitutive models. Disadvantages are high computational cost and the need to use higher order

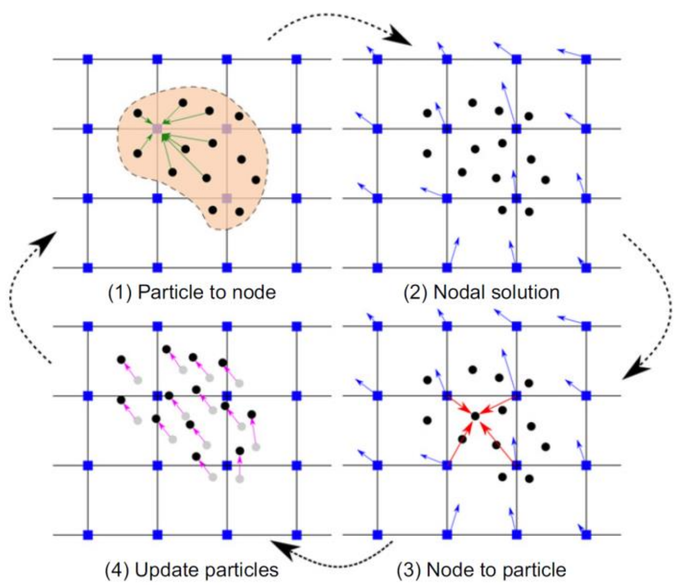


Figure 1. Computational cycle of an MPM analysis illustrating (1) the mapping of particles to grid nodes, (2) solving the relevant computation equations at the grid nodes (similar to a finite element or finite difference solution), (3) mapping the nodal displacements back to the particles, and (4) updating the position of the particles while leaving the nodes of the grid fixed (after Soga et al. 2016).

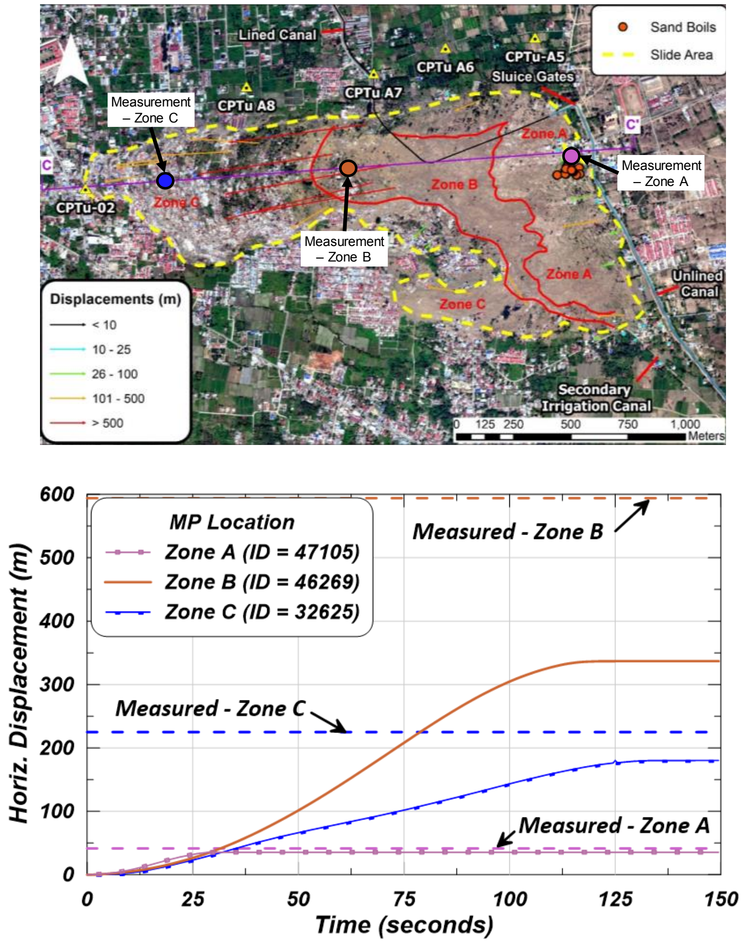
shape functions to avoid numerical errors. Yerro et al. (2019) demonstrated the use of MPM to perform a runout analysis of the Oso landslide and Lino et al. (2022) used MPM to examine static liquefaction of a tailings dam, but there have been few applications of MPM to liquefaction problems involving earth dams. One recent exception is the analyses by Talbot et al. (2024) looking at the runout of the Lower San Fernando dam. One of the reasons for the lack of liquefaction related analyses is that MPM formulations for dynamic problems, such as earthquakes, are still in development (e.g., Feng et al. 2021) and not ready to use in practice.

This study proposes to use MPM to perform post-earthquake stability analyses. In the proposed framework, a different method, such as the extensively validated combination of FLAC and the constitutive model PM4Sand, is used to evaluate liquefaction triggering within the dam and/or foundation. MPM is then used to estimate the possible deformations due to liquefied elements reaching residual strength conditions. In the proposed framework, the MPM program Anura3D (Anura3D MPM Research Community 2023) is used for the post-earthquake phase of the analysis. One advantage of the proposed approach is that both programs have been validated for their proposed use (i.e., FLAC for seismic analyses and MPM for large deformation runout analyses) and the proposed framework aligns well with current state of the practice for examining liquefaction induced deformations (i.e., using a decoupled post-earthquake stability analysis following the dynamic analysis as described by USSD 2022). One significant disadvantage is that two programs must be used to perform the analyses, but the authors are developing coupling tools to ease this process.

FINDINGS AND CONCLUSIONS

The authors are actively applying the proposed framework to multiple problems and comparing the results to traditional approaches to perform post-earthquake stability analyses. One example application of the proposed framework is the liquefaction-induced flowslides that occurred during the 2018 Palu earthquake in Indonesia (Mason et al. 2021). These flowslides were triggered by liquefaction of saturated sandy soils and while they did not occur below an earth dam, they are relevant case histories to assess the ability of the proposed framework to capture large deformations when liquefied soils reach residual strengths.

The results of one of the analyses are shown in Figure 2. For this analysis, the Petobo flowslide was modeled with Anura3D by assuming that the entire liquefiable layer reached residual strength conditions (residual strength ratio of 0.02) following the earthquake. Figure 2 compares the measured displacements at three points within the flowslide with the values from the MPM analysis. The MPM analysis was able to predict a similar extent of the flowslide and good agreement was observed between the measured displacements and the analysis results near the scarp and toe. The analyses underpredicted displacements in the central portion of the flowslide and reasons for this are still being investigated.



(a)

(b)

Figure 2. Results of the MPM analysis of the liquefaction-induced flowslide at Petobo, Palu following the 2018 Palu earthquake showing (a) map of the flowslide (after Mason et al. 2021) and (b) material point displacements at selected locations.

The MPM analyses also provide some insight into the timing of the movements across the site. The velocity of the material points in zones B and C begin to increase after approximately 12 seconds, while the deformations in zone A have reached their maximum value after about 30 seconds. Eyewitnesses to this flowslide described a delay between the strong shaking and the initiation of movements (Mason et al. 2021), which would be consistent with this slower start to large deformations. The points in zone B and C reach their maximum velocities (4.5 m/s in zone B and 1.7 m/s in zone c) after approximately 75 seconds with the velocities returning to near zero after approximately two minutes of simulation time. Sujatmiko and Ichii (2021) used a video recording from the nearby Jono Oge flowslide to estimate the velocity in the central region of the slide (similar location to zone B in this analysis) to be between 3 and 5 m/s, which is very consistent with this study.

A second example application for the proposed framework is for post-earthquake stability analyses of the hypothetical dam examined by Boulanger et al. (2015). A modified version of the dam cross-section was used in this study and is shown in Figure 3a with a clay core, gravelly sand shells, a layer of alluvium under both shells, and a downstream gravel berm. Dynamic simulations were performed using FLAC2D (Itasca 2023) and the constitutive models PM4Sand (v3.3) for the shell, berm, and alluvium and PM4Silt (v2.1) for the clay core. The simulations were performed in stages to first establish initial stress conditions, followed by shaking from the selected time history (fault normal recording from the Murdunu station for the 1999 İzmit earthquake) and a six-second period of "quiet time" to allow the model to come to rest. Following this quiet period, a post-earthquake stability analysis is performed by assigning residual strengths to the zones that were judged to liquefy (based on an excess pore pressure ratio greater than 0.7 or a shear strain greater than 5%). The undrained strength ratio in the core of the dam is reduced to 0.2 for the post-earthquake phase. Readers interested in seeing the input files for the FLAC analyses can download the files from https://github.com/jmontgomery-au/FLAC2D-ExampleDam. Boulanger et al. (2015) showed that the upstream shell of the dam was expected to become unstable for residual strength ratios less than 0.1, so this study considers residual strength ratios of 0.12 and 0.05 to determine if the MPM analyses are able to distinguish between cases with limited and large deformations.

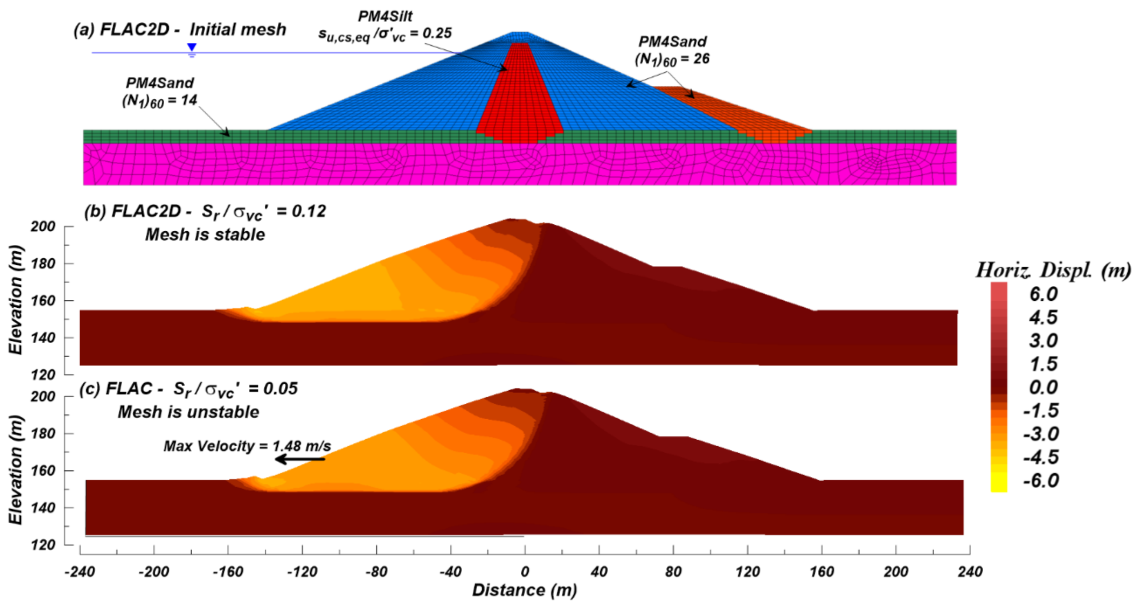


Figure 3. (a) Cross-section of a hypothetical dam (after Boulanger et al. 2015), which was used for FLAC simulations. Final deformed mesh with residual strength ratios of either (b) 0.12 or (c) 0.05. Note that the deformed mesh with the residual strength ratio of 0.05 is unstable.

The post-earthquake stability results from FLAC are shown in Figures 3b and 3c for the two residual strength ratios. For a residual strength ratio of 0.12, the upstream shell becomes unstable, but regains stability after approximately 4.0 meters of lateral displacement. The crest settlement results are shown in Figure 4 for both the dynamic and post-earthquake phases of the analyses. The crest settles approximately 1 meter during the dynamic phase of the analysis and settles an additional 2.5 meters with the higher residual strength ratio before stabilizing. With the lower residual strength ratio, the upstream shell becomes unstable (Figure 3c) and the crest settlement is approaching 4 meters when the simulation is halted due to excessive mesh deformation. The toe of the upstream shell had a horizontal velocity of 1.48 m/s at the time the simulation was halted, indicating that deformations were likely to be much higher if the simulation was able to continue.

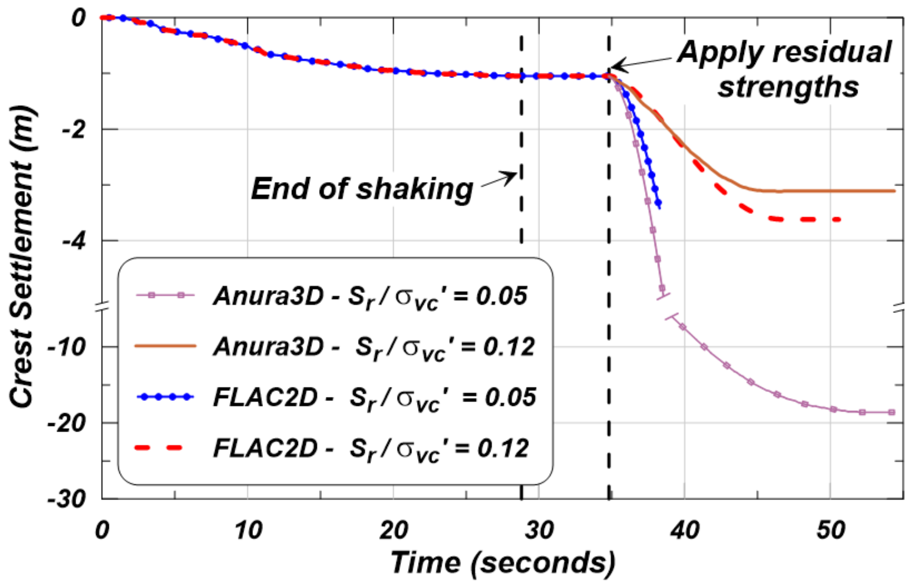


Figure 4. Crest settlement time histories from the center of the dam crest. Post-earthquake stability results are shown for both FLAC2D and Anura3D using two residual strength ratios. Note the change in scale on the y-axis.

The post-earthquake stability phase of the analyses was repeated using Anura3D. The dam geometry and regions of liquefied elements were extracted from the FLAC analyses and the liquefied regions were assigned a residual strength ratio of either 0.12 or 0.05. The other zones were assigned a Mohr-Coulomb strength similar to the drained strength, with the exception of the core, which was assigned an undrained strength ratio of 0.2 for the post-earthquake phase. The final displacement results are shown in Figure 5. The MPM simulations are able to predict the upstream slide observed in the FLAC analyses for both residual strength ratios. The simulations using the residual strength ratio of 0.12 give similar results between MPM and FLAC as displacements are small enough to avoid excessive mesh distortion. Differences between the two simulations for this case are likely due to different effective stress conditions in the two models, which could be resolved through have a method to directly map results from FLAC to the material points. The crest settlement results are also similar (Figure 4) for the higher residual strength ratio. For the lower residual strength ratio, the MPM results are able to capture the runout of the liquefied material and give a maximum crest settlement of approximately 20 meters (Figure 4) and a maximum horizontal displacement of approximately 70 meters. Both the final settlement and displacement from MPM are larger than the FLAC simulations, which were halted due to mesh distortion after approximately 5 meters of lateral displacement.

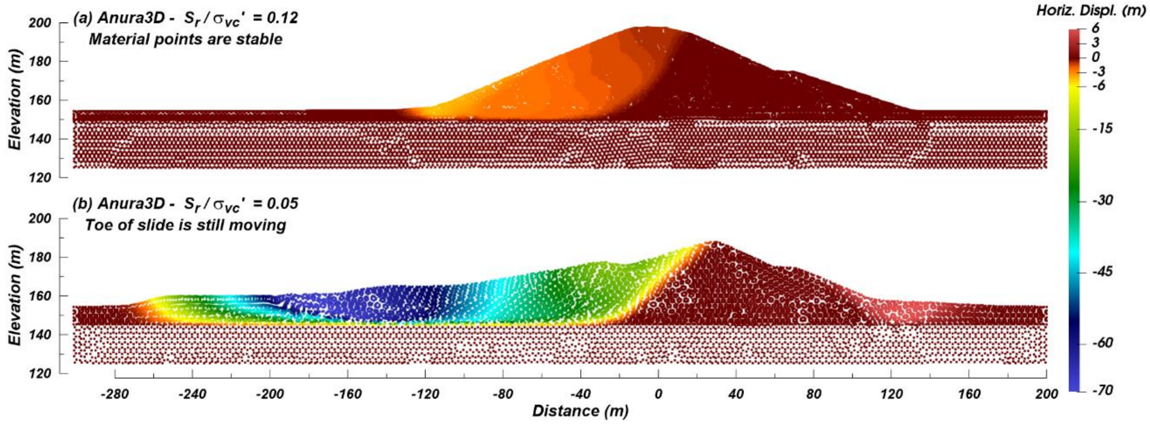


Figure 5. MPM simulations with residual strength ratios of either (a) 0.12 or (b) 0.05.

The analyses presented in this paper demonstrate the potential of MPM analyses to be used for post-earthquake stability analyses when residual strength conditions and large deformations are likely to occur. The Petobo results showed that displacements were underpredicted in certain zones, but the MPM results are far more useful than similar analyses using FLAC, which could only capture flowslide initiation and were then halted due to mesh distortion problems (Mason et al. 2021). The MPM results also give consistent velocities with those observed at a nearby flowslide, which gives additional confidence in the results. Simulations were also performed to examine the post-earthquake stability of an earth dam affected by liquefaction. The MPM and FLAC analyses show similar failure patterns, but the MPM results provide a clearer picture of the final deformed shape and expected crest settlement. The FLAC analyses are very consistent with the MPM results for the case with limited post-earthquake deformations, but the FLAC analyses cannot capture the larger deformations due to excessive mesh deformation.

Additional work is needed to validate the MPM results for case histories with both large deformations (e.g., Talbot et al. 2024) and limited deformations to show that the proposed framework can capture the range of potential behaviors. Additional work is also needed to identify the most accurate approaches to transfer information from the first stage of the analysis (FLAC2D) to the MPM analysis. Future studies should develop automated tools to transfer the information from the FLAC2D mesh to the material points to both reduce the amount of time required to perform the analyses and to improve the consistency between the two analysis stages.

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