Development of a software suite for the structural analysis and design of concrete gravity dams

A.Akman[1], Y.Arici[2], B. Binici[2], O. Kurc[2]
[1]*Vice President, ES-Proje Design&Consultancy, Turkey*
[2]*Middle East Technical University, Turkey*

ABSTRACT:

In contrast to other infrastructure, there has been very limited cooperation between the industry and academia on developing the analytical tools for the design and evaluation of dams for seismic loading. This is mostly due to the complexity of the dam behavior as well as the size of these systems precluding the diffusion of academic information to the tools used by the practicing engineer due to time constraints. With the support of the Turkish National Sciences Foundation under the academia-industry cooperation grant programme, a commercial software suite is being developed including two major features developed in the scientific literature indispensable to the realistic design and evaluation of concrete dams. Soil-structure-reservoir interaction (SSI), with an extensive development in the scientific literature, is integrated in the first part of the software, allowing the realistic analyses of 2 and 3D dam systems. This feature enables the prediction of the correct damping response on the system simulating the wave propagation effects correctly in contrast to the finite element models used in the industry. On the other hand, the evaluation of the existing dams usually requires very large scale nonlinear finite element modeling out of the scope of the general purpose analysis tools. A parallel-explicit finite element engine is the second important feature of the suite enabling the user to predict the behavior of systems with excess of millions of degrees of freedom incorporating the cracking behavior. An easy to use graphical user interface, enabling the user to easily create the models and evaluate the analysis results, forms the top framework of the suite. This pre-post processor is dam-specific, designed for users to easily create and visualize dam and valley geometries, select common design inputs and analyses assumptions, as well as easily retrieve the specific outputs used for interpretation of the analyses results.

INTRODUCTION:

In contrast to early years of cooperation between the academia and industry in the field of dam engineering (Chopra, 1978, Fenves and Chopra, 1986, USACE,1995), there has been a limited transfer of information and modeling tools from the academia to the engineering practice in the last 3 decades. This fact could mainly be attributed to the complexity of the tools and methodology generated in academia which could hardly be applied by a professional engineer due to the practical constraints. The use of these procedures and formal application required large computational resources as well as the allocation of significant time, which were deemed unpractical in the professional world. The procedures, methodologies or tools developed in academia are products of research & development, therefore lack the robustness of a commercial tool. Combined with the absence of the detailed verification/guidelines of these tools and the resource/time requirements, a significant gap in the practice between the academia and the professional world emerged. General purpose finite element models are often used for simplified modeling of the dam systems with very significant modeling assumptions in the professional world. On the other hand, a significant literature on soil-structure interaction was developed for addressing the wave propagation issue on large domains for addressing the SSI part of the structural problem. For detailed modeling of the nonlinear behavior of the large structures, numerical procedures to simulate very large mathematical models were developed in conjunction with very capable constitutive models simulating the cracking in unreinforced concrete structures (Rots, 1988, Lee and Fenves, 1998).

Design or evaluation of dams has almost always been conducted using general purpose finite element tools in the last 3 decades. Linear evaluation tools were developed and used due to the constraints on the model size; 2D monolith modeling was almost universal (USACE, 2007). The solution of dam systems using a 40-50K node finite element models have only been possible in the last couple of years which still requires solution times easily in excess of days. Even now, the limitations of the FE tools force the professionals to use approximate linear evaluation tools, such as the CID procedure (Ghanaat, 2004), to assess the system at hand. On top of these limitations, significant simplifications in the problem formulation had to be assumed for the modeling of the system in general purpose tools, such as the modeling assumptions for the foundations or the 2D analyses choice in order to limit the number of DOFs. The radiation damping which is a major factor in these problems is included in the models very crudely and erroneously, reservoir interaction is considered using approximations. As summarized above, in the overall, a crude approximation to the real conditions had to be used for the performance estimation of gravity dams due to these constraints (Chopra, 2008).

The details of a new software suite, developed to overcome these shortcomings in the practice, are the main subject of this paper. With the support of the Turkish National Sciences Foundation, a cooperation between Es-Proje, a design&consulting company and the Middle East Technical University is formed in order to develop the required tools for robust, realistic analyses and simulation of concrete gravity dams based on the state-of-the-art in the academic sphere. The goals of this project are two-folds: First and the foremost goal is to enable tools capable of accurate modeling of soil-reservoir-structure interaction for dam systems and develop these tools for large-scale simulations. Two different modules, one prepared for the “exact” solution of the 3D soil-structure-reservoir interaction problem in the frequency domain and the second, prepared for solving very large nonlinear problems using parallel processing are being developed. The second goal of the project is to develop a robust graphical user interface which enables the pre and post-processing for these modules with capabilities specifically tuned for the user in professional practice. In such a fashion, the user should spend majority of the time on selecting or adjusting design choices, not in the calibration or fine tuning of the software at hand.

A short description of the deficiencies of the structural analyses conducted for dam systems is presented as an introduction in the next section. The theoretical background of the software development is presented next, with a focus on the two different modules planned for the software. The graphical user interface is treated in the fourth section of the manuscript. The summary and conclusions from the work conducted so far are presented in the last section of the study.

LIMITATIONS OF STRUCTURAL ANALYSES FOR DAM SYSTEMS:

As mentioned above, numerous simplifications are employed during the analyses of concrete gravity dams for managing the size and the complexity of the problem at hand. These simplifications are summarized with the major implications given below:

Theoretical Issues: A number of problems are unavoidable using general purpose finite element models for the simulation of the soil-structure-reservoir interaction of dam systems.

- Radiation Damping: Radiation damping is very poorly represented in these models. Using massless foundations or absorption elements/springs are only approximations to the solution. Damping is very often very conservatively applied, leading to unexpectedly high response quantities and the accompanying design requirements on the system,
- Reservoir Interaction: Reservoir interaction is generally included using Westergaard masses or reservoir elements. The use of reservoir elements requires extensive calibration for each case for validation purposes. The use of Westergaard masses are known to lead to misrepresenting results the more flexible the dam system is.

Modeling Associated Issues: A number of assumptions are often made to limit the size of the problem which may lead to erroneous predictions.

- 2D/3D Modeling: 2D modeling assumptions is generally used for determining the response of a dam in order to reduce the size of the analysis model. This choice, while predicated on the presence of expansion joints, i.e. the monolith style construction of dams, is mostly for practical reasons. The 3D response, on the other hand, is significantly different from the 2D response as demonstrated by the frequency response curves given for some represantitive systems in Figure 1. The frequency response for a 80m tall dam located in a 320m wide valley (Legend, 2X) is significantly different from the 2D response, predicted using both the rigorous SSI formulation and the massless model (USACE, 1995). The time history analyses conducted for various ground motions shows the difference in demand quantities can exceed 100% for these frequency response functions.

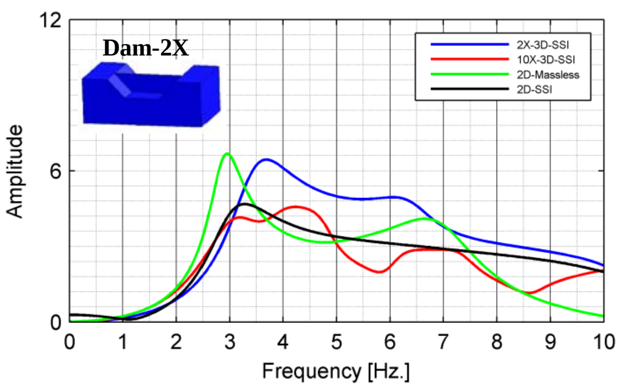


Figure 1 Frequency Response Function, Dam in a Moderate Width Valley, Comparison with 2D Analyses

- Modeling Limitations: The general purpose finite element programs are limited by the implicit solvers. Paralellization of the matrix solution to multiple processors is not efficient after 2 processors which virtually limit the size of the problems you can solve with these software. The current computational power does not allow for the solution of large models in excess of 50000 nodes using these solvers.

Practical Issues: Most of the common questions posed by the dam engineer cannot be easily answered by general purpose programs due to major limitations:

- Nonlinear Behavior: Given the limitation on the problem size, large scale nonlinear models can hardly be solved using existing software with implicit solvers. The element sizes are too large for this task for todays computational resources.
- Pre-Post Processing: Each dam project is a different challenge on a different terrain model. Hence, locating or optimizing the shape is a significant challenge for existing location data. Post-processing is generally non-standard for different general purpose tool. It is often very cumbersome to obtain the results of analyses in a diluted form appropriate for decision making on design/evaluation.

The realistic simulation of dam behavior also requires the consideration of the stochastic nature of the design or evaluation process, embodied on the capacity side with uncertainty in material properties and on the demand side with uncertainties in loading conditions. In the simplest sense, the realistic prediction of the possible response of a dam system requires a significant number of trials, for materials or loading conditions. In case of a design process, this corresponds to a considerable time spend on a trial and error process with numerous geometries, material properties or loading conditions. A robust GUI that can 1) speed-up the trial and error process by easy manipulation of the geometry or the material properties, and 2) generate easily comprehensible diluted engineering output, is a definite requirement for practical use.

SOFTWARE FRAMEWORK:

The framework prepared under the cooperation of METU and Es-Proje is comprised of three main parts:

1) A frequency domain module for simulating the response of concrete gravity dams in a realistic setting with theoretically robust modeling of soil-structure-reservoir interaction effects,
2) A time domain module for simulating the nonlinear response of concrete gravity dams using very large models with parallel computation on multiple processors and explicit solver,
3) A graphical user interface which enables manipulation of both modules, easy entry/change of model constituents and fast post-processing capabilities.

Each module is described briefly in the following sections.

Frequency Domain Module:

The frequency domain procedure and the tool utilized for this analysis is based on the generalization of the EACD-08 program (Wang and Chopra, 2008) for concrete gravity dams. The realistic response of a dam-rock-reservoir system is obtained in this methodology with a robust representation of the radiation damping and the reservoir-structure interaction in a frequency domain setting. A flow chart of the methodology is provided in Figure 2. The module requires the generation of separate element structures for the foundation, dam and the reservoir. The foundation elements are boundary elements: modeling of the whole terrain is not required as the radiation effect is represented using these boundary elements.

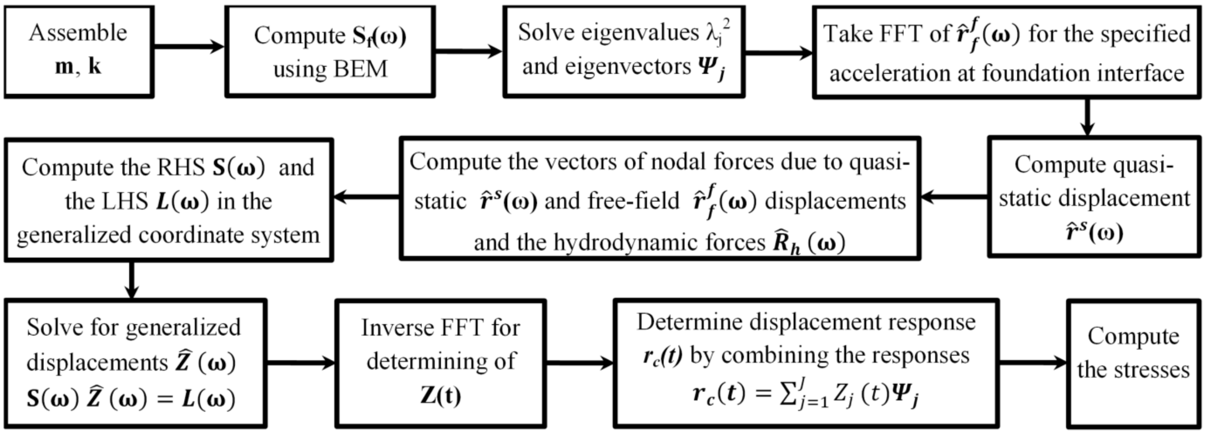


Figure 2 Flowchart for Frequency Domain Analyses of 3D Dam-Reservoir-Foundation Interaction

The radiation damping for a concrete gravity dam in a three dimensional valley is reflected appropriately in this module as given in Figure 3 . For a typical 80m tall cross section located in a 320m wide canyon, the variation of the response is represented in terms of the frequency response functions of the displacement at the crest of the dam. The reduction in the peak of the response quantity for different dam foundation modulus/structure modulus ratios is easily visible. The difference in the frequency response compared to a 2D model is also evident in this figure. The 3D response of this system is significantly different from a 2D system as demonstrated in this example.

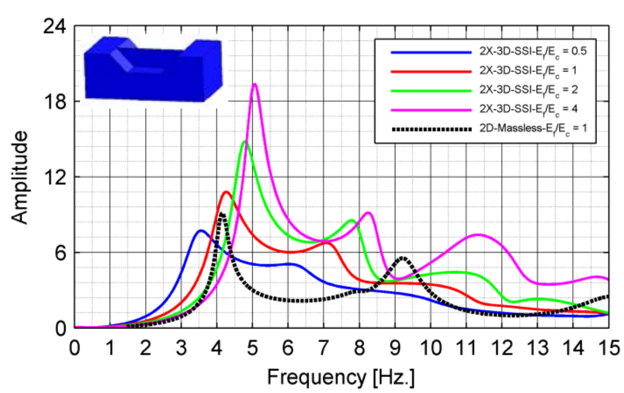


Figure 3 Frequency Response for a Typical Gravity Dam with Increasing Foundation Stiffness

Time Domain Module:

A time domain module using explicit integration techniques was prepared in order to utilize the power of multiple processors for solving the vibration problem for very large dam models. The explicit algorithm used in the module relies on an effective modification of the equation of motion to use multiple computational cores at the same time. The algorithm [1] requires significantly small time steps for avoiding iterations in the analysis.

$$\frac{\mathbf{1}}{\Delta \boldsymbol{t}^{\mathbf{2}}}[\boldsymbol{M}]\{\boldsymbol{D}\}_{\boldsymbol{n}+\mathbf{1}} = \{\boldsymbol{R}^{\textit{Dış}}\}_{\boldsymbol{n}} - [\boldsymbol{K}]\{\boldsymbol{D}\}_{\boldsymbol{n}} + \left[\frac{\mathbf{2}}{\Delta \boldsymbol{t}^{\mathbf{2}}}\boldsymbol{M} - \frac{\mathbf{1}}{\Delta \boldsymbol{t}}\boldsymbol{C}\right]\{\boldsymbol{D}\}_{\boldsymbol{n}} - \left[\frac{\mathbf{1}}{\Delta \boldsymbol{t}^{\mathbf{2}}}\boldsymbol{M} - \frac{\mathbf{1}}{\Delta \boldsymbol{t}}\boldsymbol{C}\right]\{\boldsymbol{D}\}_{\boldsymbol{n}-\mathbf{1}} \tag{1}$$

In this equation ***M***,***C*** and ***K*** represent the mass, damping and stiffness matrices, respectively. The displacement of the system at time ***n+1*** is calculated from only former displacement values. A number of elements are tested and made available for use in the modeling of the dam structures. Linear and quadratic brick elements as well as wedge elements are available. Appendages or special appurtenant structures can be modeled using beam and shell elements which are also available.

The module is based on object-oriented data structure comprised of various data classes (Figure 4). The domain class, as given below, processes the input to conduct the analyses using the three other classes: the Model Builder, Analyzer and the Puggkernel. The PuggKernel is responsible for adding new capabilities to the engine if required. Written in C++, it is prepared for use in distributed computing on multiple computers or a single multi-processor cluster.

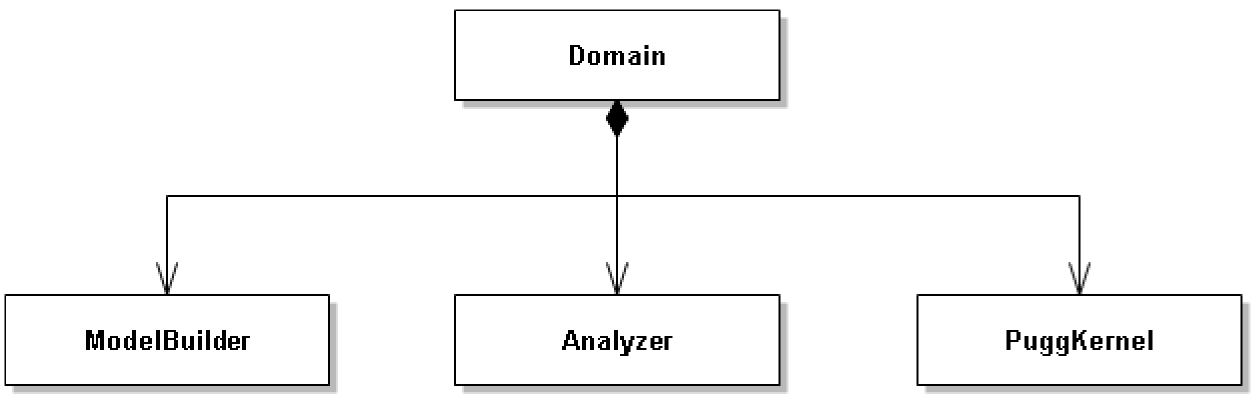
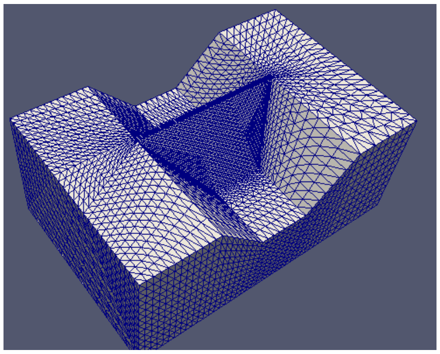


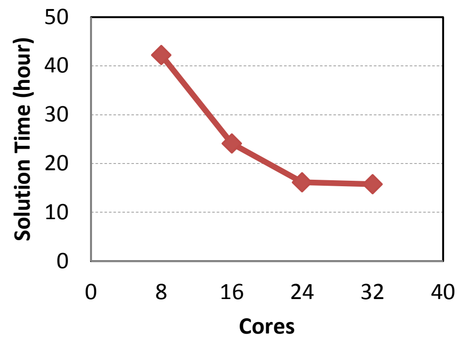
Figure 4 Data Classes in Software

The module includes a MUMPS solver (Amestoy et al., 2000) for the solution of statically posed large problems. It can utilize standard Newton-Raphson or improved Newton Raphson procedures (Cook et al., 2001) to solve nonlinear problems. In time domain, the module includes an explicit Newmark solution algorithm which is used to solve a different part of the model in different processors in a parallel fashion. The DistributedExplicitNewmark class uses different objects for partitioning the model using the ParMETIS library.

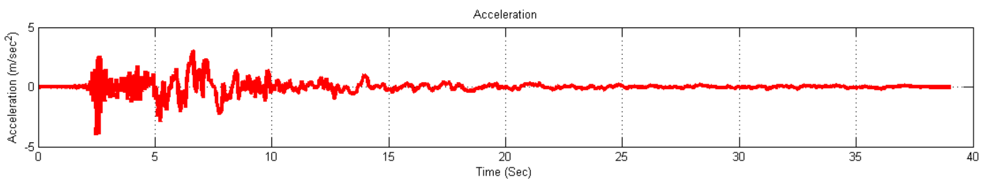
The scaling advantage of the module is presented in the following figure on a simple demonstrative dam model comprised of 186000 elements (Figure 5a). A time history analysis is conducted for a total of 40 seconds (Figure 5c). Using 32 cores, the problem was solved in around 15 hours using 3 year old Intel Xeon E5630 processors. The scalability of the problem appears to have reached an optimal value at 24 processors which is reasonable given the small size of the problem (Figure 5b). Larger problems would benefit more from the use of 32 or more cores.



(a) Sample Model, 186000 Elements



(b) Scaling for Increasing Processor Cores



(c) Time Dependent Loading

Figure 5 Scaling Performance of the Module on a Sample Dam System

GUI Module:

A web base graphical user interface is developed for pre and post-processing of the aforementioned two modules. The software is implemented as a web based interface that can manipulate many worker applications that are distributed over a network of computers or virtual machines. Visualization is performed at the web browser using the JavaScript library three.js which drives the WebGL engine (Jackson, 2015). Mesh generation is handled by the GMSH mesh generation library (Geuzaine and Remacle, 2015). Analysis is delegated from this interface to the analysis modules. The application represents a cloud-based workflow, and can be run at a remote computer or a local computer, with the possibility of assigning analyses to client machines or servers or the local computer.

Backend of the implementation consists of many server applications which are coded using *Node.js*, mesh generator (GMSH and structural mesh generator) and the analysis modules. *Node.js* is a framework that allows developers to build server side applications (besides other type of applications) with JavaScript. *Node.js* spawns single-threaded processes which are event driven and non-blocking which make it especially suitable for data intensive real-time applications. The structure of the server of the presented framework is presented in Figure 6.

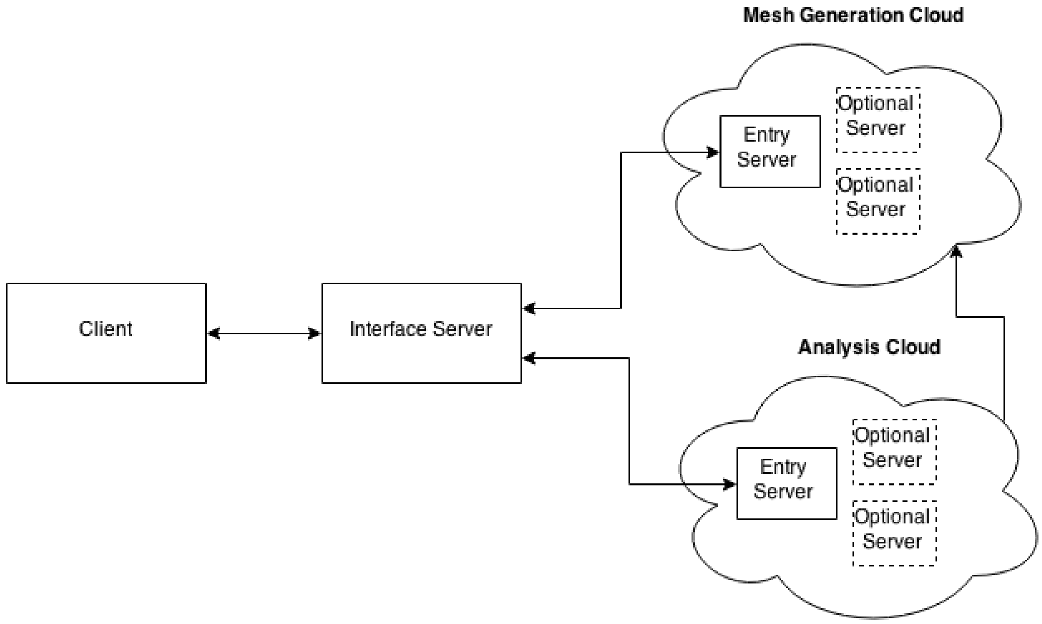


Figure 6 Structure of the Client-Server Interaction

The definition of geometry and mesh generation can be conducted on a local or client machine. A sample screenshot of the model generation window is provided as follows (Figure 8). The model allows for simple text based input for generation of simple dam geometries as given in Figure 7a, with options for changing the material or geometric properties. This simple shape can be used for locating the dam geometry in the specified valley or terrain profile. The WebGL based engine and a generated mesh in 3D coordinates is presented in Figure 7b. The engine can operate on the server side sending and receiving package information efficiently for displaying the model on the client side. The engine can also be operated completely on the client side as well. Testing conducted so far did not reveal any significant operational differences between these two approaches. The transfer mechanism works smoothly with 60 fps speed and minimal lag for displaying results.

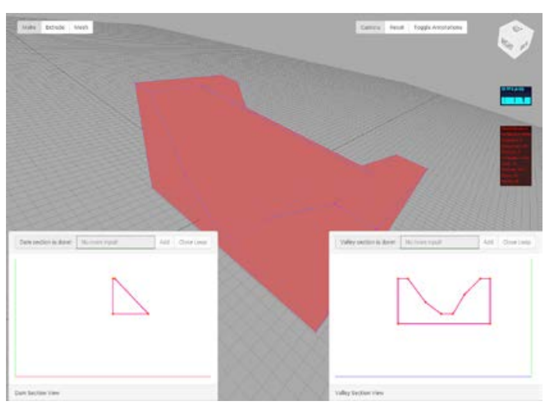


Figure 7 GUI at Different Levels

SUMMARY:

The cooperation of Es-Proje and METU undertaken with the support of the Turkish National Sciences Foundation seeks to transfer the knowledge developed in the academic sphere to the professional one by developing a set of tools that enables practical approach to the structural analyses problem of dams with a robust technical background. Three main modules are developed for this purpose. The first of the analyses modules enables the use of robust solution of the dam-reservoir-structure interaction problem modeling the radiation damping correctly. The second analyses module enables the use of very large scale structural models, in excess of a couple of hundred thousand nodes, making realistic nonlinear analyses and performance prediction (i.e. dam break) possible. An overarching third module is prepared to manipulate the aforementioned components for pre and post-processing purposes specifically designed for the inputs and outputs required by the dam engineer.

Acknowledgement

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