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MONTE CARLO SIMULATIONS OF COUPLED TRANSIENT SEEPAGE FLOW AND COMPRESSIVE STRESS IN LEVEES *

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Abstract. The purpose of this research is to compare the results from two different computer programs of flow analyses of two levees at Port Arthur, Texas where rising water of a flood from Hurricane Ike occurred on the levees. The first program (Program 1) is a two-dimensional (2-D) transient finite element program that couples the conservation of mass flow equation with accompanying hydraulic boundary conditions with the conservation of force equations with accompanying x and y displacement and force boundary conditions, thus yielding total head, x displacement, and y displacement as unknowns at each finite element node. The second program (Program 2) is a 2-D transient finite element program that considers only the conservation of mass flow equation with its accompanying hydraulic boundary conditions, yielding only total head as the unknown at each finite element node. Compressive stresses can be computed at the centroid of each finite element when using the coupled program. Programs 1 and 2 were parallelized for high performance computing to consider thousands of realisations of the material properties. Since a single realisation requires as much as one hour of computer time for certain levees, the large realisation computation is made possible by utilising HPC. This Monte Carlo type analysis was used to compute the probability of unsatisfactory performance for under seepage, through seepage, and uplift for the two levees. Respective hydrographs from the flood resulting from Hurricane Ike were applied to each levee. When comparing the computations from the two programs, the most significant result was the two programs yielded significantly different values in the computed results in the two clay levees considered in this research.

Key words: coupled transient seepage/stress analysis, finite element method, high performance computing

AMS subject classifications. 65Y05, 35J66, 76S05

1. Introduction. Practising engineers commonly perform transient finite element seepage analyses that account only for seepage due to hydraulic boundary conditions but do not account for forces applied to the levee with resulting stresses in the levee due to rising water [1]. In clay levees, excess pore pressures beyond those from just hydraulic boundary conditions are developed from stresses in the levee soil as the river rises. Seepage design information can therefore be incorrectly estimated without considering these excess pore pressures. A detailed geotechnical explanation of the proper use and limitations of transient seepage in levees is given in [2, 3]. The trend in academic research as in [2, 3] and in commercial software documentation such as in [4] is that a fully coupled transient seepage/stress analysis is needed for clay levees. Other studies describing the importance of coupling in modelling seepage flow are [5, 6, 7, 8].

However, only one or just a few values of each soil parameter are often used in current research, although there is significant variation in these values. Unique features of this research are that 6000 realisations of the soil properties are considered, and specific failure modes were investigated. Thus, a two-dimensional (2-D) finite element transient seepage program (SEEP2D-TRAN-HPC) that considers only Darcian seepage flow and a 2-D coupled transient finite element seepage/structural plane strain program (SEEP2D-COUPLED-HPC)

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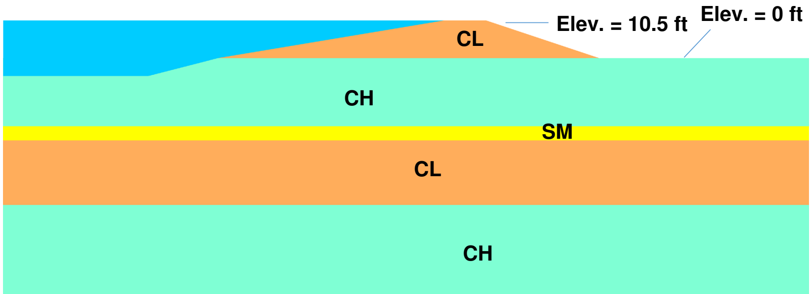

Fig. 3.1. *First levee.*

were written for parallel, high performance computing (HPC) to analyse the failure modes of under seepage, through seepage, and uplift using 6000 realisations of material properties described in [9]. This allows a Monte Carlo type analysis to investigate the fraction of the realisations that produced unsatisfactory performance using criteria for the three failure modes. This is equivalent to the probability of unsatisfactory performance (PUP) for each failure mode.

When comparing independent simulations in a previous study, we found that 6000 realisations of the material properties were sufficient to yield estimates of the probability of unsatisfactory performance within one percentage point. This result was consistent over 30 levees representing a wide variety of geometries and soil types. Based on these results, we chose to use 6000 realisations of the material properties in this study.

2. Purpose. The purpose of this study was to compare the difference in results from SEEP2D-TRAN-HPC and SEEP2D-COUPLED-HPC for under seepage, through seepage, and uplift using as a measure the PUP for each failure mode using two levees from Port Arthur, Texas as test levees. This paper reports the results of the study, gives the equations used, and describes the computational challenges encountered in developing a successful parallel coupled transient seepage/compressive stress program.

3. Levees. Two levees in Port Arthur, Texas are considered in this paper. Figure 3.1 shows the first levee where the respective soil types as defined by the Unified Soil Classification System (USCS) and are as follows: CL - low plasticity clay, CH - high plasticity clay, SM - silty sand, and SP - poorly graded sand. The figure shows the water level at the elevation of the crown (10.5 ft (3.2 m)), but the transient solution applies a hydrograph from the flood resulting from Hurricane Ike. The land side water level is held at the ground surface elevation of 0 ft. Figure 3.2 shows the hydrograph of the flood on the gulf side of the levee where simulation time = 0 days when the water level from the gulf reaches 0 ft (0 m). The hydrograph was developed using the Coastal Storm Modelllng System (CSTORM) [10], the coupled Advanced Circulation (ADCIRC) programs [11, 12], and the Steady-State Spectral Wave (STWAVE) model [13, 14].

Figures 3.3 and 3.4 show the second levee and its hydrograph. As before, the usable part of the hydrograph starts at the elevation of the ground surface on the land side of the levee (7.5 ft (2.29 m)). However, on the gulf side, the water level exceeds the elevation of the crown of 16.5 ft (5.03 m) which results in over-topping. For seepage inside the levee, the hydrograph used in the computations is capped at 16.5 ft (5.03 m).

4. Equations for transient seepage in the saturated zone. Transient flow where only conservation of mass and hydraulic boundary conditions from the rising water on the levee are considered is governed by

$$\frac{\partial}{\partial x}\left(k_{xs}\frac{\partial\phi}{\partial x}\right)+\frac{\partial}{\partial y}\left(k_{ys}\frac{\partial\phi}{\partial y}\right)=m_v\frac{\partial\phi}{\partial t} \tag{4.1}$$

where k_{xs} is the saturated hydraulic conductivity in the x direction, k_{ys} is the saturated hydraulic conductivity in the y direction, ϕ is total head, m_v is the volumetric compressibility of the soil, x is the x coordinate, y is the y coordinate, and t is time. As discussed earlier, a coupled formulation where both hydraulic boundary conditions and the structural loads applied to the levee by the water, causing stresses, strains, and displacements of the soil, is preferred, especially for clay levees. There are many levels of sophistication available for this coupled analysis

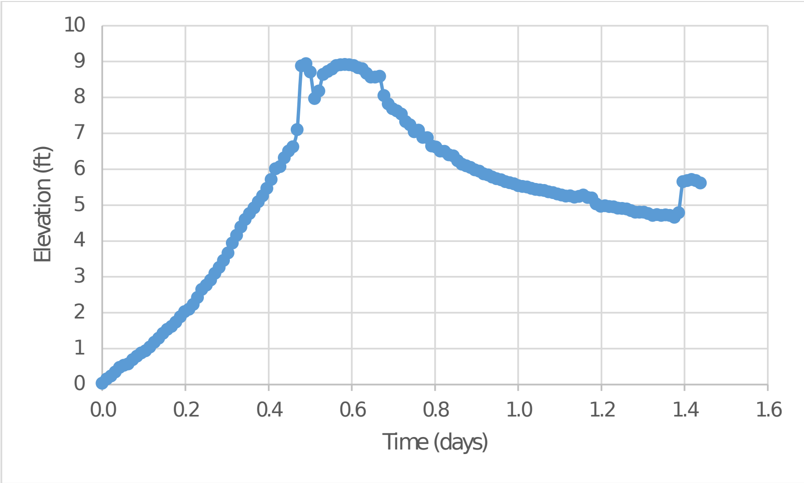

FIG. 3.2. *Hydrograph for the first levee.*

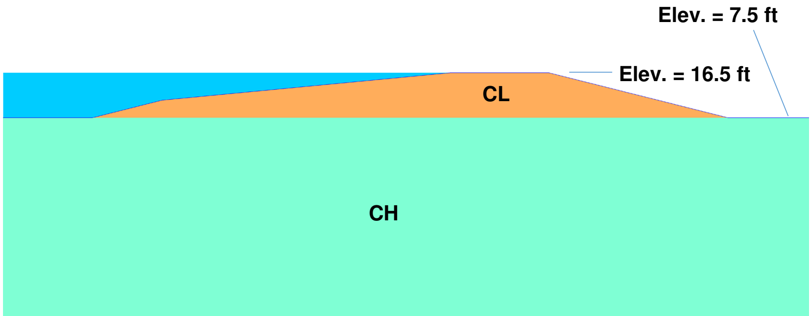

FIG. 3.3. *Second levee.*

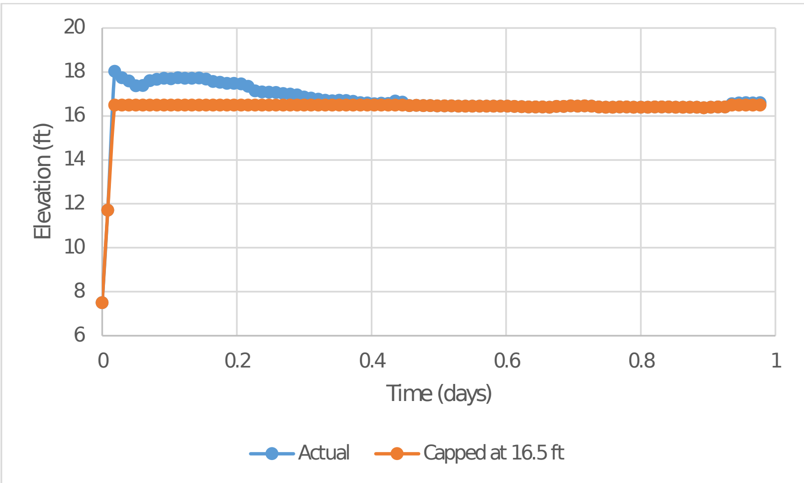

FIG. 3.4. *Hydrograph for the second levee.*

as described in [4]. The initial version of SEEP2D-COUPLED-HPC uses a simple plane strain constitutive model for the soil and an uncoupled unsaturated flow assumption. Later versions can easily have more options.

Conservation of forces inside a finite element is given by

$$\{\sigma\} + \gamma_w(\phi - y)\left\{\begin{array}{c} 1 \\ 1 \\ 0 \end{array}\right\} = [C]\{\epsilon\}$$

where

$$\{\sigma\} = \left\{\begin{array}{c} \sigma_{xx} \\ \sigma_{yy} \\ \tau_{xy} \end{array}\right\} \tag{4.2}$$

and

$$\{\epsilon\} = \left\{\begin{array}{c} \epsilon_{xx} \\ \epsilon_{yy} \\ \gamma_{xy} \end{array}\right\} = \left\{\begin{array}{c} \frac{\partial u}{\partial x} \\ \\ \frac{\partial v}{\partial y} \\ \\ \frac{\partial v}{\partial x} + \frac{\partial u}{\partial y} \end{array}\right\}$$

where σ_{xx} is the normal stress in the x direction, σ_{yy} is the normal stress in the y direction, τ_{xy} is the shearing stress, ϵ_{xx} is the normal strain in the x direction, ϵ_{yy} is the normal strain in the y direction, γ_{xy} is the shearing strain, u is the displacement in the x direction, v is the displacement in the y direction, γ_w is the density of water, and $[C]$ is the soil plane strain constitutive matrix given by

$$[C] = \frac{E}{(1+\nu)(1-2\nu)}\left[\begin{array}{ccc} 1-\nu & \nu & 0 \\ \nu & 1-\nu & 0 \\ 0 & 0 & \frac{1-2\nu}{2} \end{array}\right] \tag{4.3}$$

where E is Young's Modulus and ν is Poisson's Ratio.

The coupled governing equation for conservation of flow in the saturated zone is

$$\frac{\partial}{\partial x}\left(k_{xs}\frac{\partial \phi}{\partial x}\right) + \frac{\partial}{\partial y}\left(k_{ys}\frac{\partial \phi}{\partial y}\right) = \frac{\partial}{\partial t}\left(\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y}\right) \tag{4.4}$$

5. Equations for transient seepage in the unsaturated zone. The pore pressures from SEEP2D-TRAN-HPC, SEEP2D-COUPLED-HPC, and a steady-state version of these programs (SEEP2D-SS-HPC) are input into slope stability programs similar to [15] where negative pore pressures are not considered. To keep equivalent sophistication for purposes of comparison, negative pore pressures ($\phi < y$) are not considered here. Thus conservation of force in a finite element in the unsaturated zone is given by (see Eq. 4.2 for comparison)

$$\{\sigma\} = [C]\{\epsilon\} \tag{5.1}$$

Also, for a finite element in the unsaturated zone, the uncoupled version of conservation of flow is used. Starting with the equation for the suction head, ψ,

$$\psi = y - \phi \tag{5.2}$$

conservation of flow is modelled by Richards equation [16],

$$\frac{\partial}{\partial x}\left(k_r k_{xs}\frac{\partial \phi}{\partial x}\right) + \frac{\partial}{\partial y}\left(k_r k_{ys}\frac{\partial \phi}{\partial y}\right) = \frac{\partial \theta}{\partial t} = -\frac{d\theta}{d\psi}\frac{\partial \phi}{\partial t} \tag{5.3}$$

where k_r is the relative hydraulic conductivity ($0 < k_r \leq 1$), and θ is the moisture content. Also, k_r and θ are functions of ψ resulting in Eq. 5.3 being a difficult non-linear equation to solve.

6. Moisture content and relative hydraulic conductivity. The equations for moisture content and relative hydraulic conductivity as given in [17] are used in this work.

6.1. Moisture content. Moisture content is modeled by

$$\theta(\psi) = B(\psi)\frac{\theta_s}{\left\{\ln\left[e+\left(\frac{\psi}{\beta}\right)^n\right]\right\}^m} \tag{6.1}$$

$$B(\psi) = 1 - \frac{\ln\left(1+\frac{\psi}{C_r}\right)}{\ln\left(1+\frac{1000000}{C_r}\right)} \tag{6.2}$$

where θ_s is the saturated moisture content; and β, C_r, m, and n are soil parameters.

6.2. Relative hydraulic conductivity. Using the change of variables,

$$\psi = e^z \tag{6.3}$$

$$k_r\left(\psi\right) = \frac{\int_{\ln\psi}^{\ln 1000000}\frac{\theta(e^z)-\theta(\psi)}{e^z}\theta'\left(e^z\right)dz}{\int_{\ln\varepsilon}^{\ln 1000000}\frac{\theta(e^z)-\theta(\psi)}{e^z}\theta'\left(e^z\right)dz} \tag{6.4}$$

$$\begin{aligned}\theta'(\psi) = &- B(\psi)\frac{mn\theta_s\left(\frac{\psi}{\beta}\right)^{n-1}}{\beta\left\{\ln\left[e+\left(\frac{\psi}{\beta}\right)^n\right]\right\}^{m+1}\left[e+\left(\frac{\psi}{\beta}\right)^n\right]}\\ &-\left[\frac{1}{\ln\left(\frac{1000000}{C_r}\right)\left(\psi+C_r\right)}\right]\left[\frac{\theta_s}{\left\{\ln\left[e+\left(\frac{\psi}{\beta}^n\right)\right]\right\}^m}\right]\end{aligned} \tag{6.5}$$

where ε is a small positive number. Eq. 6.4 is numerically integrated to obtain a value for k_r.

7. Unsatisfactory performance criteria. Unsatisfactory performance for the three failure modes of under seepage, through seepage, and uplift is determined by provided criteria. There are two unsatisfactory performance criteria for each failure mode, and they are limit state (LS) and engineering practice (EP). The LS criteria are typically used for forensic analysis and extreme events, while the EP criteria are used in the design stage.

7.1. Under seepage. A positive value of vertical exit gradient, i_v, at the toe is used for testing under seepage. This is computed by selecting two node points with the same x value at the toe of the levee as shown in Fig. 7.1 and using

$$i_v = \frac{\phi_1 - \phi_2}{y_2 - y_1} \tag{7.1}$$

where ϕ_1 is the total head of the first selected node and beneath the ground surface, ϕ_2 is the total head of the second selected node and on the ground surface, y_1 is the y coordinate of the first selected node, and y_2 is the y coordinate of the second selected node.

The critical vertical exit gradient, i_{cv}, at the toe is computed from

$$i_{cv} = \frac{\gamma_s}{\gamma_w} - 1 \tag{7.2}$$

where γ_s is the density of the saturated soil. The limit state criterion for unsatisfactory performance for under seepage is

$$i_v \geq i_{cv} \tag{7.3}$$

The engineering practice criterion for unsatisfactory performance for under seepage is

$$i_v \geq 0.5 \tag{7.4}$$

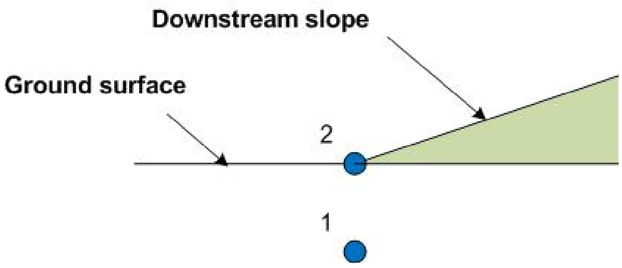

FIG. 7.1. *Nodes for vertical exit gradient computation.*

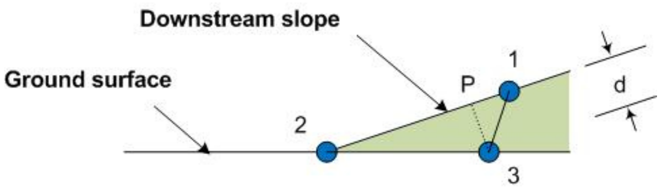

FIG. 7.2. *Nodes for perpendicular exit gradient computation.*

7.2. Through seepage. The exit gradient, i_p, near the toe and perpendicular to the land side slope of the levee at the toe is used for testing through seepage. From Fig. 7.2, this research uses

$$i_p = \frac{\phi_3 - \phi_P}{d} \tag{7.5}$$

The three node points, 1, 2, and 3, are determined from the nodes of the finite element mesh in the embankment at the toe.

The limit state criterion for unsatisfactory performance of through seepage at the toe is given by

$$i_p \geq i_{cv} \cos\theta \tag{7.6}$$

where θ is the angle between the land side slope of the levee and the ground surface. The engineering practice criterion for unsatisfactory performance of through seepage at the toe is given by

$$i_p \geq 0.5 \cos\theta \tag{7.7}$$

7.3. Uplift. Uplift is computed at the toe typically beneath the confining layer of the levee (see Fig. 7.3) to check the factor of safety with respect to heave or uplift. The factor of safety for uplift is

$$f_{up} = \frac{\gamma_s \left(y_B - y_A\right)}{\gamma_w \left(\phi_A - y_A\right)} \tag{7.8}$$

which represents a ratio of weight divided by the uplifting force. The limit state criterion for unsatisfactory performance of uplift is given by

$$f_{up} \leq 1 \tag{7.9}$$

and the engineering practice criterion for unsatisfactory performance of uplift is

$$f_{up} \leq 1.5 \tag{7.10}$$

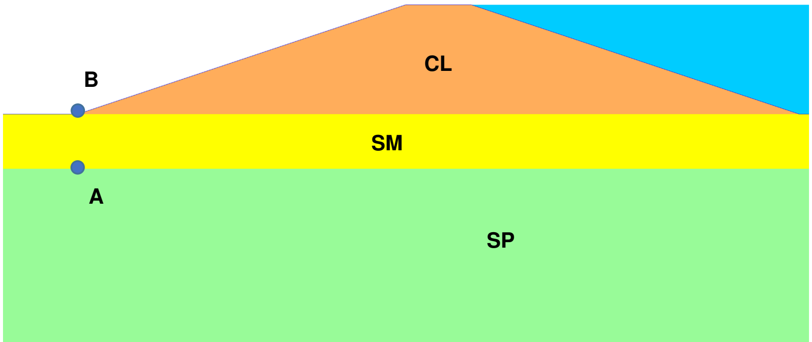

Fig. 7.3. *Points A and B for uplift computation.*

Table 9.1
Current configuration for the Onyx system.

Node Type	Compute Nodes	Cores/Node	Memory/Node
Standard	4810	44	121 Gb
GPU	32	22	246 Gb
Bigmem	4	44	997 Gb
KNL	32	64	90 Gb

8. Initial and boundary conditions. The initial conditions are that the water level is at the ground surface, and only the weight of each finite element of the levee is the applied force. Also, the bottom of the levee is fixed for no x or y displacement and considered impervious to water flow. Boundary conditions for flow are as follows: (1) Total head is applied to the gulf side of the levee as dictated by the provided hydrograph. (2) The elevation of the ground surface on the land side of the levee is the total head applied on this boundary. (3) The land side slope of the levee is an exit face where the phreatic surface (pore pressure = 0) that intersects this downstream slope must be determined by an iterative solution. (4) For forces, the water from the hydrograph is applied as water pressure on the levee.

9. Computational details and challenges. The governing equations for coupled flow and displacement with three degrees of freedom per node (u, v, and ϕ) were implemented into the finite element program, SEEP2D-COUPLED-HPC. SEEP2D-TRAN-HPC with only ϕ as a degree of freedom was also written. For the coupled solution, only the weight of the levee is first applied with the water at the ground surface to obtain initial displacements of the nodes. Then for a given small time increment, Δt, the water level is advanced a small amount using the hydrograph and a new increment of displacement and total head for each node is computed. The non-linear nature of the equations requires iteration at each time step to achieve a solution.

The finite element meshes of the two levees were generated on the PC using SEEP2D [18, 19] in the Groundwater Modeling System [20]. Once generated, these mesh files were uploaded to a large HPC system. SEEP2D-TRAN-HPC and SEEP2D-COUPLED-HPC are written in Fortran and use the Message Passing Interface (MPI) [21] for parallelization. The HPC system used is a Cray XC40/50 at the ERDC DSRC named “Onyx” [22]. Table 9.1 shows the current configuration of Onyx. Six thousand MPI processes were run on 6000 cores with only collecting the results of the success or failure of each realisation needing communication.

Each non-linear iteration at each time step creates a system of simultaneous, linear equations to be solved. For SEEP2D-TRAN-HPC, this system of equations is symmetric and positive-definite. Thus, the conjugate gradient method [23] works very well. However, for SEEP2D-COUPLED-HPC, this system of simultaneous, linear equations is nonsymmetric and lacks the positive-definite quality. An iterative solver (bi-CG stabilized [23]) was first tried without success. A banded direct solver was then implemented which solved the equations but took significantly more computer time.

The system of non-linear equations for SEEP2D-TRAN-HPC is notoriously difficult to solve. This difficulty is even more acute when running SEEP2D-COUPLED-HPC. Many researchers use Newton’s method [24], while

Table 10.1

Probability of unsatisfactory performance for the first levee for under seepage, through seepage, and uplift for hydraulic boundary conditions only.

Time (days)	Elevation (ft)	Under LS	Under EP	Through LS	Through EP	Uplift LS	Uplift EP
0.200	2.044	0.000	0.000	0.000	0.000	0.000	0.030
0.300	3.624	0.000	0.000	0.000	0.000	0.000	0.030
0.400	5.571	0.000	0.000	0.000	0.000	0.000	0.030
0.479	8.882	0.000	0.000	0.000	0.000	0.000	0.030
0.500	8.714	0.000	0.000	0.000	0.000	0.000	0.030
0.600	8.900	0.000	0.000	0.000	0.000	0.000	0.030
0.700	7.675	0.000	0.000	0.000	0.000	0.000	0.030
0.800	6.627	0.000	0.000	0.000	0.000	0.000	0.030
1.000	5.548	0.000	0.000	0.000	0.000	0.000	0.030
1.200	4.969	0.000	0.000	0.000	0.000	0.000	0.030

others use the Picard iteration method [25]. Still others add line search techniques to accelerate the convergence to a solution. An advantage of transient solutions is that decreasing Δt makes the solution easier to converge. This work chose a simple combination of the Picard iteration, a small Δt, and a modified convergence criterion to obtain successful convergence for both levees tested.

The convergence criteria for a given non-linear iteration often used is

$$\max_{j=1}^{N} \left| \phi_j^{k-1} - \phi_j^{k} \right| \leq \varepsilon \tag{9.1}$$

where N is the number of node points of the finite element mesh, j is the node point number, ϕ_j^{k-1} is the total head at node, j, for iteration $k-1$, ϕ_j^k is the total head at node, j, for iteration k, and ε is a small number. The problem with Eq. 9.1 is that the iterations oscillate between different worst nodes and convergence is never achieved. This work successfully used

$$\sum_{j=1}^{N} \frac{\left| \phi_j^{k-1} - \phi_j^{k} \right|}{N} \leq \varepsilon \tag{9.2}$$

which smooths out the oscillation weakness in Eq. 9.1.

10. Results. Each core with its realisation of the material properties is run and returns either a 0 for satisfactory performance or a 1 for unsatisfactory performance for each failure mode. These 0's and 1's are then collected and summed for each respective failure mode and divided by 6000. Table 10.1 gives results for the first levee from SEEP2D-TRAN-HPC (only hydraulic boundary conditions considered), Table 10.2 gives results for the first levee from SEEP2D-COUPLED-HPC (coupled seepage/compressive stress), Table 10.3 gives results for the second levee from SEEP2D-TRAN-HPC, and Table 10.4 gives results for the second levee from SEEP2D-COUPLED-HPC.

11. Analysis. The following observations are made:

- When stresses in the levee were not considered, there is no appreciable change in the calculations of flow in the levee (Tables 10.1 and 10.3).
- When accounting for force and hydraulic boundary conditions in a coupled analysis, drastic increases of the PUP for under seepage and uplift occurred (Tables 10.2 and 10.4).
- The very rapid increase in the water level between time = 0 and time = 0.1 days in the second levee caused a rapid increase in pore pressures that then dissipated slowly as the water level stayed relatively constant. This is predicted behaviour in that excess pore pressures build up and slowly decrease over time. It also explains why PUP for under seepage and uplift gradually decreased although the water level of the flood remained almost constant.
- Through seepage did not encounter any PUP because of the slowness of water flow in the embankment.

Table 10.2

Probability of unsatisfactory performance for the first levee for under seepage, through seepage, and uplift for coupled seepage/compressive stress.

Time (days)	Elevation (ft)	Under LS	Under EP	Through LS	Through EP	Uplift LS	Uplift EP
0.200	2.044	0.000	0.000	0.000	0.000	0.000	0.051
0.300	3.624	0.033	0.386	0.000	0.000	0.000	0.078
0.400	5.571	0.488	0.976	0.000	0.000	0.000	0.127
0.479	8.882	0.999	1.000	0.000	0.000	0.000	0.219
0.500	8.714	0.988	1.000	0.000	0.000	0.000	0.238
0.600	8.900	0.941	1.000	0.000	0.000	0.000	0.297
0.700	7.675	0.471	0.959	0.000	0.000	0.000	0.278
0.800	6.627	0.126	0.504	0.000	0.000	0.000	0.238
1.000	5.548	0.012	0.074	0.000	0.000	0.000	0.183
1.200	4.969	0.001	0.013	0.000	0.000	0.000	0.157

Table 10.3

Probability of unsatisfactory performance for the second levee for under seepage, through seepage, and uplift for hydraulic boundary conditions only.

Time (days)	Elevation (ft)	Under LS	Under EP	Through LS	Through EP	Uplift LS	Uplift EP
0.100	16.500	0.000	0.000	0.000	0.000	0.000	0.029
0.200	16.500	0.000	0.000	0.000	0.000	0.000	0.029
0.300	16.500	0.000	0.000	0.000	0.000	0.000	0.029
0.400	16.500	0.000	0.000	0.000	0.000	0.000	0.029
0.500	16.459	0.000	0.000	0.000	0.000	0.000	0.029
0.600	16.441	0.000	0.000	0.000	0.000	0.000	0.029
0.700	16.456	0.000	0.000	0.000	0.000	0.000	0.029
0.800	16.403	0.000	0.000	0.000	0.000	0.000	0.029
0.900	16.384	0.000	0.000	0.000	0.000	0.000	0.029
1.000	16.500	0.000	0.000	0.000	0.000	0.000	0.029

Table 10.4

Probability of unsatisfactory performance for the second levee for under seepage, through seepage, and uplift for coupled seepage/compressive stress.

Time (days)	Elevation (ft)	Under LS	Under EP	Through LS	Through EP	Uplift LS	Uplift EP
0.100	16.500	0.268	0.997	0.000	0.000	0.268	1.000
0.200	16.500	0.135	0.950	0.000	0.000	0.135	1.000
0.300	16.500	0.082	0.829	0.000	0.000	0.082	1.000
0.400	16.500	0.055	0.664	0.000	0.000	0.055	1.000
0.500	16.459	0.033	0.459	0.000	0.000	0.033	1.000
0.600	16.441	0.023	0.306	0.000	0.000	0.023	1.000
0.700	16.456	0.017	0.221	0.000	0.000	0.017	0.999
0.800	16.403	0.007	0.102	0.000	0.000	0.007	0.998
0.900	16.388	0.004	0.063	0.000	0.000	0.004	0.997
1.000	16.500	0.005	0.083	0.000	0.000	0.005	0.997

12. Conclusions. The challenge of obtaining a stable solution of coupled flow/compressive stress in a HPC environment performing 6000 realisations of material properties was successfuly met, despite the need to solve a non-linear system of equations at each time step. The results of the research showed that a coupled analysis is essential for considering failure modes of under seepage, through seepage, and uplift in clay levees. Further, if the resulting pore pressures at the nodes of the finite element mesh for clay levees are to be input into slope stability programs, the coupled analysis is also essential for a more accurate representation of the real-world phenomenon of slope failure. Further research is needed if a faster iterative solver instead of the slow direct solver is desired for the coupled program. The computer runs for the coupled option took as long as one hour, indicating that this type of analysis requires HPC resources to perform.

REFERENCES

[1] F. T. Tracy, T. L. Brandon, and M. K. Corcoran, *Transient seepage analyses in levee engineering practice*, Technical Report TR-16-8, U.S. Army Engineer Research and Development Center, Vicksburg, MS, http://acwc.sdp.sirsi.net/client/en_US/search/asset/1050667, 2016.

[2] T. L. Brandon, *Use and misuse of transient seepage analyses in levee engineering practice*, Proc. of the 62nd Annual Geotechnical Engineering Conf., University of Minnesota, Minneapolis, Minnesota, February 28, 2014.

[3] D. R. VandenBerge, J. M. Duncan, and T. L. Brandon, *Limitations of transient seepage analyses for calculating pore pressures during external water level changes*, J. of Geotechnical and Geoenvironmental Engineering, 141, 2015.

[4] GEOSLOPE International, *Stress-deformation modeling with SIGMA/W*, http://downloads.geo-slope.com/geostudioresources/books/8/0/6/sigma%20modeling.pdf, 2013.

[5] C. Meena, T. V. Praveen, I. S. Parvathi, *Coupled seepage–stress analysis of selected roller-compacted concrete gravity dam with upstream impervious layer considering the seepage behavior of interface thickness*, Indian Geotechnical J., 8, 2019.

[6] B. Peng and J. Li, *A three-field coupled model for seepage failure*, Procedia Engineering, 126, pp. 377-381, 2015.

[7] Y. Chen, R. Hu, W. Lu, D. Li, and C. Zhou, *Modeling coupled processes of non-steady seepage flow and non-linear deformation for a concrete-faced rockfill dam*, Computers and Structures, 89 (13–14), pp. 1333-1351, 2011.

[8] K. Fujisawa, D. Niina, A. Murakami, and S. Nishimura, *Coupled problem of saturated-unsaturated seepage flow and internal erosion of soils*, 4th Asia Pacific Conf. on Unsaturated Soils, Newcastle, NSW, Australia, Nov. 23-25, 2009.

[9] M. T. Schultz, F. T. Tracy, G. S. Ellithy, D. W. Harrelson, J. L. Ryder, and M. K. Corcoran, *Characterizing the reliability of earthen levees using system response curves derived from uncertainty analysis of geotechnical simulation models*, Proc. of the U.S. Society of Dams Conf., Miami, FL, http://ussd2019.conferencespot.org/65175-ussd-1.4163582/t001-1.4164397/2f-1.4164424/a051-1.4164437/an051-1.4164438#tab_0=1, April 30–May 4, 2017.

[10] T. C. Massey, T. V. Wamsley, and M. A. Cialone, *Coastal storm modeling – system integration*, Proc. of the 2011 Solutions to Coastal Disasters Conf., Anchorage, Alaska, pp. 99-108, 2011.

[11] ADCIRC Team, *ADCIRC coastal storm modeling – system integration*, ADCIRC Utility Programs, http://adcirc.org/home/related-software/adcirc-utility-programs/, 2019.

[12] R. A. Luettich Jr., J. J. Westerink, and N. W. Scheffner, *ADCIRC: an advanced three-dimensional circulation model for shelves, coasts, and estuaries*, Technical Report DRP-92-6, U.S. Army Engineer Research and Development Center, Vicksburg, MS, 1992.

[13] J. M. Smith, A. R. Sherlock, and D. T. Resio, *STWAVE: steady-state spectral wave model user's manual for STWAVE, version 3.0*, ERDC/CHL SR-01-1, U.S. Army Engineer Research and Development Center, Vicksburg, MS, 2001.

[14] T. C. Massey, M. E. Anderson, J. M. Smith, J. Gomez, and R. Jones, *STWAVE: steady-state spectral wave model user's manual for STWAVE, version 6.0*, ERDC/CHL SR-11-1, U.S. Army Engineer Research and Development Center, Vicksburg, MS, 2011.

[15] S. G. Wright, *UTEXAS4, a computer program for slope stability calculations, educational version*, http://www.ce.utexas.edu/prof/wright/UTEXASED4/UTEXASED4%20Manual.PDF, 2004.

[16] L. A. Richards, *Capillary conduction of liquids through porous mediums*, J. of Physics, 1, pp. 318-333, 1931.

[17] D. G. Fredlund and A. Xing, *Equations for the soil-water characteristic curve*, Canadian Geotechnical J., 31, pp. 521-532, 1994.

[18] N. L. Jones, *SEEP2D primer*, GMS documentation, Environmental Modeling Research Laboratory, Brigham Young University, Provo, UT, 1999.

[19] F. T. Tracy, *User's guide for a plane and axisymmetric finite element program for steady-state seepage problems*, Instruction Report IR K-83-4, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS, 1983.

[20] GMS team, *Groundwater Modeling System (GMS)*, www.aquaveo.com/GMS, 2019.

[21] Message Passing Interface Forum, *MPI: A message-passing interface standard, version 3.0*, http://www.mpi-forum.org/docs/mpi-3.0/mpi30-report.pdf, 2012.

[22] ERDC DSRC, *onyx HPC computer system*, https://www.erdc.hpc.mil/docs/onyxUserGuide.html, 2019.

[23] Y. Saad, *Iterative Methods for Sparse Linear Systems*, SIAM, Philadelphia, 2003.

[24] C. T. Kelley, *Solving nonlinear equations with Newton's method*, SIAM, 2003.

[25] S. Mehl, *Use of Picard and Newton iteration for solving nonlinear ground water flow equations*, Ground Water, 44, pp. 583-594, 2006.

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