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On NDA practices for evaluating liquefaction effects

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ABSTRACT

This paper discusses three aspects of nonlinear dynamic analysis (NDA) practices that are important for evaluating the seismic performance of geotechnical structures affected by liquefaction or cyclic softening: (1) selection and calibration of constitutive models, (2) comparison of NDA results using two or more constitutive models, and (3) documentation. The ability of the selected constitutive models and calibration protocols to approximate the loading responses important to the system being analyzed is one of several technical factors affecting the quality of results from an NDA. Comparisons of single element simulations against empirical data for a broad range of loading conditions are essential for evaluating this factor. Critical comparisons of NDAs using two or more constitutive models are valuable for evaluating modeling uncertainty for specific systems and for identifying modeling limitations that need improvement. The utility of an NDA study depends on the documentation being sufficiently thorough to facilitate effective reviews, advance best practices, and support future reexaminations of a system's seismic performance.

INTRODUCTION

Non-linear dynamic analyses (NDAs) are widely used in engineering practice to evaluate the seismic performance of geotechnical structures affected by liquefaction or cyclic softening. NDAs can provide an improved basis for estimating deformations over simplified methods that do not account for dynamics or are limited to idealized geometries or conditions. This can be particularly important for any performance-based evaluation of liquefaction effects. However, the quality of results from an NDA study depend on several technical and nontechnical factors, including the selection and calibration of the constitutive models, the limitations of the numerical modeling procedures, the quality of the site characterization work, the selection of the input ground motions, the expertise of the analyst, the allotment of sufficient time and resources for completing the work, and the quality of the documentation and review processes.

The approaches used to select, calibrate, and evaluate constitutive models for an NDA can differ significantly in research and practice. Regardless of the approach, confidence in the NDA results depends on the ability of the selected constitutive models to represent the loading responses important to the system being analyzed. The critical examination of constitutive model performance via single element and system level studies is not only important for individual applications, but also important for promoting progressive improvements in the models and modeling procedures.

This paper examines three aspects of NDA practices that are important for evaluating the seismic performance of geotechnical structures affected by liquefaction or cyclic softening: (1) selection and calibration of constitutive models, (2) comparison of NDA results using two or more constitutive models, and (3) documentation. The first section discusses several considerations in the selection, calibration, and evaluation of constitutive models in engineering practice. The second section discusses the value of critical comparisons of NDA results obtained using two or more constitutive models for evaluating modeling uncertainty and promoting improvements in the models and their calibration protocols. The third section discusses NDA documentation practices for facilitating effective reviews, advancing best practices, and providing value to clients and owners.

CONSTITUTIVE MODEL CONSIDERATIONS

The evaluation of seismic performance for a geotechnical structure, whether deterministic or probabilistic, involves synthesizing information from tasks regarding: geology, site characterization, property estimation, seismic hazard characterization, analysis models for estimating seismic responses, damage assessment (e.g., cracking, need for repairs), consequence assessment (e.g., loss of life, direct or indirect economic losses), and performance objectives. The uncertainties associated with each of these tasks propagate through the evaluation process and are manifested as bias or dispersion in the results. The evaluation process is often iterative, with individual tasks refined whenever the potential impacts on final decisions warrant the additional engineering time and cost. These components and steps in the seismic evaluation of a system are schematically illustrated in Figure 1.

Analysis models for computing seismic responses may range in complexity from equivalent static procedures to NDAs of various degrees of sophistication. Equivalent static procedures or NDAs with simplistic constitutive models have significant limitations regarding the mechanisms they can model and the level of insight into system responses they can provide, as well as a greater potential for bias or dispersion in predictions of performance. Nonetheless, these simpler engineering models can be sufficient for reaching sound decisions if their limitations are recognized and reasonably accounted for through appropriate conservatism.

The motivation for using NDAs with more realistic, complete, or sophisticated constitutive models is the expectation that they should provide improved insights, reduced bias, and reduced dispersion. NDAs with more sophisticated constitutive models (e.g., bounding surface plasticity

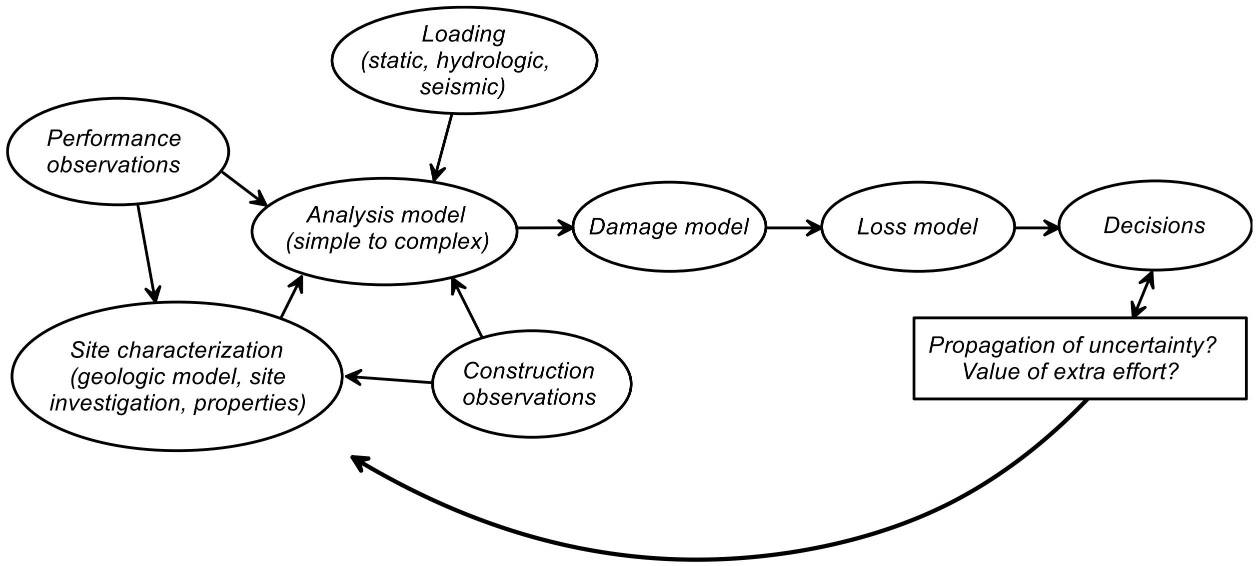

Figure 1. Components and steps in the evaluation of seismic deformations.

or multiple yield surface models), when well performed, can provide more realistic responses and improved insights that cannot be obtained by equivalent static methods or NDAs with simpler constitutive models that do not account for dilatancy and cannot simulate cyclic mobility. For example, there are a number of uncoupled "cycle-counting" models that start with a Mohr Coulomb model and modify the strength and stiffness parameters during cyclic loading based on an internal accounting of the cyclic loading history via empirical correlations (e.g., Dawson et al. 2001). Cycle-counting models focus on getting the first-order effects of liquefaction triggering on strength and stiffness and have the advantage of being relatively easy to use. However, cycle-counting models and other simple models that cannot simulate cyclic mobility can produce misleading and unrealistic responses for systems that are strongly dependent on cyclic mobility (e.g., the transmission of shear stresses after triggering of liquefaction). On the other hand, some stress-strain behaviors of liquefying soils are not captured by even the most sophisticated models; e.g., most models greatly underestimate post-liquefaction reconsolidation strains and thus underestimate their contribution to ground surface settlements (e.g., Ziotopoulou and Boulanger 2013). Thus, the appropriateness of any constitutive model for an NDA depends on its capabilities relative to the mechanisms and stress-strain behaviors that are important to a particular system's seismic performance.

Key Properties and Model Calibration

A constitutive model for liquefiable soil is more versatile if it can reasonably approximate the range of mechanical properties and stress-strain behaviors that are commonly most important to the performance of geotechnical structures. The key properties and stress-strain behaviors for many systems fall into the four categories listed below.

- Stiffness and damping. These properties are important for the dynamic response of a system and thus directly affect the cyclic loading imposed on the soils in the system. These properties are commonly represented in terms of a maximum (small-strain) shear modulus (G_{max}) and equivalent secant shear moduli (G) and damping ratios for a range of uniform cyclic strain amplitudes (i.e., G_{max}, and G/G_{max} and damping ratio versus cyclic strain amplitude).
- Cyclic resistance to liquefaction triggering. The cyclic resistance ratio (CRR) describes the loading levels that trigger liquefaction and the associated onset of larger strains. The CRR depends on the failure criterion, number and amplitude of undrained loading cycles (e.g., CRR versus number of uniform loading cycles N), overburden stress (e.g., as represented by a K_σ relationship), and initial static shear stress ratio (e.g., as represented by a K_α relationship).
- Cyclic mobility after liquefaction triggering. Cyclic mobility refers to how rapidly strains accumulate during cyclic loading after liquefaction has been triggered, and thus is important to the estimation of deformations for systems that remain stable after earthquake loading. Cyclic mobility is commonly evaluated by comparing simulated post-triggering stress-strain responses with those from laboratory tests with and without initial static shear stresses, for site-specific samples or similar soils under similar loading conditions.
- Residual shear strength (S_r). The post-liquefaction strength is important to the stability of a geotechnical structure. Estimates of S_r have large uncertainty for several reasons, including the effects of sample disturbance for any attempted laboratory tests, questions regarding the potential for void redistribution in the field (a system response problem), and the shortage of quality case histories across the range of conditions important to practice. Residual strengths are commonly estimated using case history-based correlations, which are generally conservative (especially when extrapolating). One common practice is to use the case history based S_r values for evaluating post-earthquake stability, while using higher strengths during dynamic shaking to account for the possibility that much of the strength loss may occur as excess pore pressures diffuse after the end of strong shaking and thus imposing the lower strength during strong shaking may incorrectly underestimate the shear stresses that can be transmitted during that shaking. This approach, which has been common in practice for several decades, is discussed in more detail by Naesgaard and Byrne (2007) and Boulanger et al. (2014).

Other stress-strain behaviors, such as post-liquefaction reconsolidation strains or shearing under partially drained loading conditions, can be equally important for some systems. However, a constitutive model's general utility is more significantly limited by any strong biases or limitations in how it approximates the properties and stress-strain behaviors listed above.

The calibration of a constitutive model for liquefiable soils is most commonly based on engineering correlations to cone penetration test (CPT), Standard Penetration Test (SPT), and shear wave velocity (V_s) data. Most analyses represent specific strata or subzones with equivalent uniform properties that are estimated using representative values for the various in situ test measurements (e.g., Montgomery and Boulanger 2016). The uncertainty associated with the selection of a representative value is usually indirectly accounted for by selecting upper and lower range values for use in sensitivity analyses. A sound geologic model for site-specific depositional processes can be vital for the specification of model zones and selection of representative properties. Calibration of the constitutive model must consider the range of overburden stresses and initial static shear stress ratios of importance to any specific application. If a constitutive model does not adequately approximate how the stress-strain behavior of a liquefiable soil varies with these initial stress conditions, it may be necessary to use smaller subzones covering a smaller range of initial stress conditions for the purpose of model calibration (e.g., repeating the calibration for narrower ranges of overburden stress).

Calibration of a constitutive model to cyclic laboratory test data is relatively rare in practice, except for special cases where sample disturbance can be managed (e.g., silty sands or sandy silts with specific loading histories). Even if sampling disturbance effects on CRR are a concern, laboratory tests may help in evaluating post-triggering strain accumulation rates (i.e., cyclic mobility). For these cases, it is helpful if the strain accumulation rate for the constitutive model can be adjusted to approximate the laboratory test data or cover a range of estimated rates. The single-element simulations shown in Figure 2 illustrate how the post-triggering cyclic mobility of the PM4Sand model (version 3; Boulanger and Ziotopoulou 2015, Ziotopoulou and Boulanger 2016) can be adjusted to reflect strain accumulation rates from laboratory tests or evaluate sensitivity of a NDA to this aspect of model calibration. These simulations are for undrained, uniform cyclic loading in direct simple shear (DSS) for a sand at a relative density (D_R) of 55% and initial vertical effective stress (σ'_{vc}) of 1 atm. The stress-strain responses after an excess pore pressure ratio ($r_u = \Delta u/\sigma'_{vc}$) of 100% has been triggered, show peak shear strains increasing by about 0.9%, 1.6%, and 2.1% per cycle for the cases with the dilatancy parameter n^b equal to 0.5, 0.25, and 0.125 in Figures 2a, 2b, and 2c, respectively.

The approach to calibrating a constitutive model against laboratory test data, when available, requires consideration of how well the constitutive model captures the effects of different loading paths. For example, the CRR determined from a set of cyclic triaxial tests would be multiplied by a factor of about 0.67 to obtain an estimate of the CRR for simple shear loading beneath level ground with an in situ K_o of 0.5 and by another factor of about 0.9 to account for bidirectional horizontal shaking. A constitutive model calibrated to the cyclic triaxial CRR will not necessarily produce reasonable estimates of the simple shear CRR or vice versa, and certainly will not account for the effects of bidirectional shaking (which is indirectly accounted for in a 2D

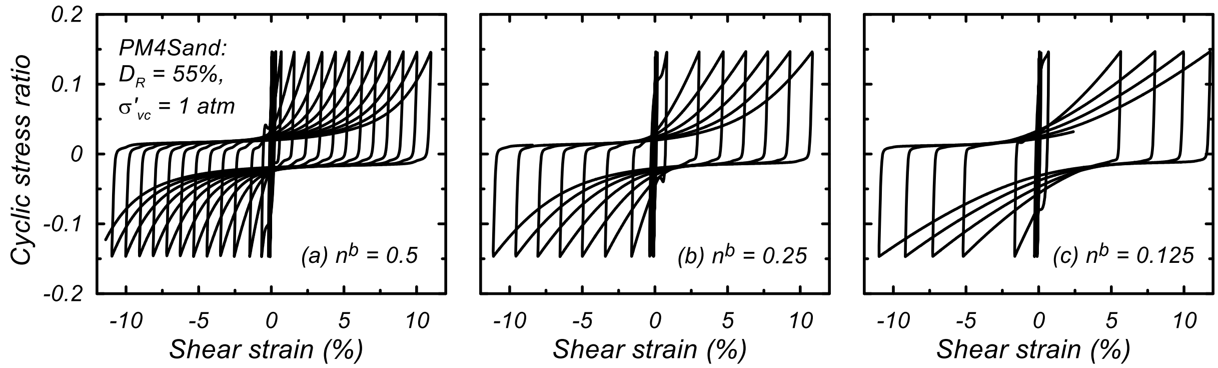

Figure 2. Simulated single element response for undrained cyclic DSS of PM4Sand with post-triggering cyclic mobility adjusted using the dilation parameter n^b.

NDA by using appropriately reduced CRRs). If simple shear loading is more representative of loading conditions at the system level, it is better to calibrate the constitutive model to the estimated simple shear CRR (with its adjustment for bidirectional shaking) than to the measured triaxial CRR. In these cases, the stress paths and cyclic mobility measured in cyclic triaxial tests may not be directly comparable to those simulated by the calibrated constitutive model. The measured cyclic triaxial responses, however, are still valuable for guiding model calibration, provided it is recognized that the objective is not a one-to-one comparison of the responses under triaxial loading.

More generally, the approach to model calibration in practice is philosophically different from a traditional mechanics approach that focuses on measuring fundamental input parameters or requires a specific set of laboratory tests to define those parameters. In practice, it is important to focus on estimating the key properties and stress-strain behaviors (e.g., G/G_{max} and damping, CRR, cyclic mobility, S_r) by the best means available (e.g., laboratory tests or engineering correlations), and then calibrating the constitutive model to honor those estimated properties and stress-strain behaviors (via iterative adjustment of input parameters), rather than focus on directly measuring fundamental input parameters and then largely accepting the resulting constitutive behaviors. For example, it would be ill-advised to focus on determining the representative initial void ratio (e_o) and critical state line (CSL) for a naturally deposited stratum with all its heterogeneity, followed by letting those parameters dictate the undrained critical-state shear strength ($s_{u,cs}$) via the constitutive model. Instead, the focus should be placed on estimating the $s_{u,cs}$ (which may be intended to represent S_r in an NDA) using the best available information (whether by laboratory testing or case history correlations), and then selecting the e_o and CSL parameters to ensure that the constitutive model produces the desired $s_{u,cs}$ response. This latter approach can be applied with the PM4Sand constitutive model, as illustrated in Figure 3, using the following sequence of steps: (1) values are selected for the initial D_R, critical state line parameter Q, and critical state stress ratio M, (2) the mean effective stress at critical state p'_{cs} is computed as 2.0 times the desired $s_{u,cs}$ divided by M, and (3) the remaining critical state line parameter R is computed so that the model,

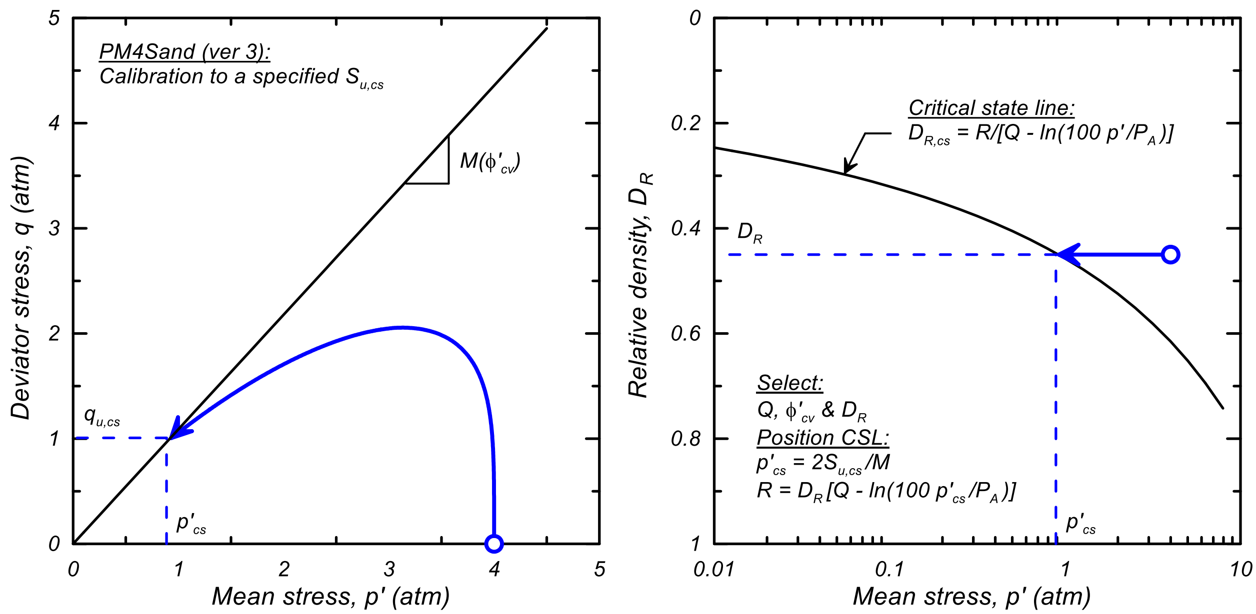

Figure 3. Approach for calibrating PM4Sand to a specified undrained critical state shear strength.

given the other specified parameters, returns the desired $s_{u,cs}$. This approach has the outcome that the undrained shear resistance produced by the constitutive model at large strains is essentially independent of the specified D_R because the critical state line is determined conditional on that D_R. An advantage of this approach to constitutive model calibration is that it reinforces the need to interpret results of an NDA as conditional on the estimated key properties and stress-strain behaviors (rather than on sometimes-abstract input parameters), and facilitates evaluating the effects of uncertainty in those key properties and stress-strain behaviors (rather than the effects of uncertainty in input parameters) on system responses.

Evaluation and Validation at the Element and System Levels

Evaluation of a constitutive model should include suites of single element simulations covering the broad range of loading paths that may be important to system level responses. These suites of simulation responses, given any baseline model calibration, can be compared to the trends predicted by empirical correlations to identify areas of significant differences or consistencies. A first level evaluation is whether there are strong differences between simulated and expected stress-strain behaviors that could lead to strongly biased NDA results. A second level of evaluation is assessing and documenting the potential biases that a particular constitutive model may have for different types of loading conditions. The documentation of representative stress-strain behaviors or biases (relative to expected behaviors or correlations) across a broad range of loading conditions is valuable for guiding users in the calibration of a constitutive model for specific applications and for promoting improvements in the constitutive models. A constitutive model may be considered

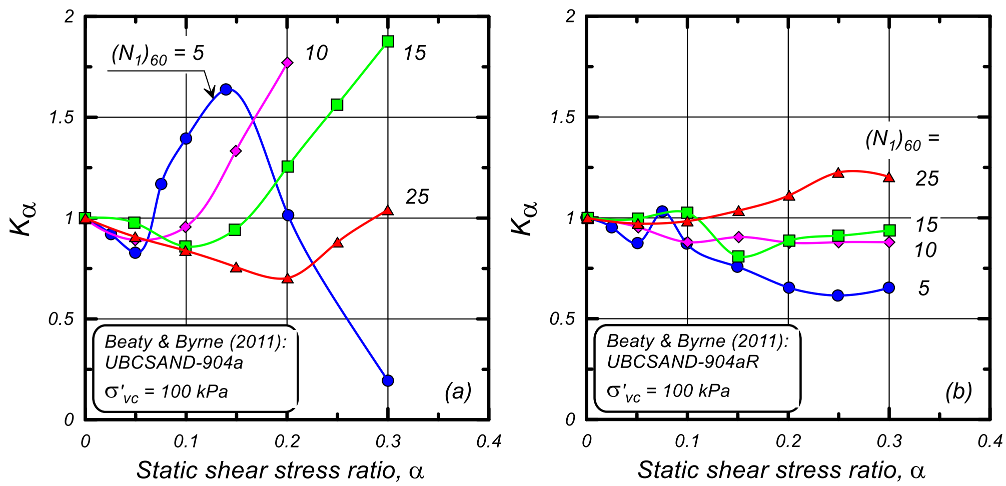

Figure 4. Single element simulation results for undrained DSS loading using two versions of UBCSAND: (a) 904a, and (b) 904aR (after Beaty & Byrne 2011).

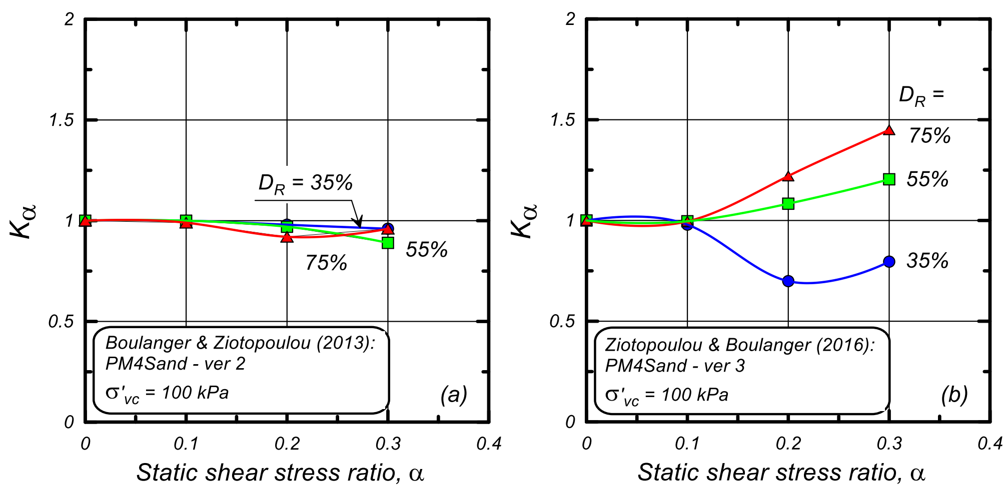

Figure 5. Single element simulation results for undrained DSS loading using two versions of PM4Sand: (a) version 2, and (b) version 3.

validated for certain applications if it meets the needs of users, but the more general purpose of an evaluation is understanding or quantifying potential biases or limitations for the broader range of loading conditions for which the model might be used.

Examples of constitutive model improvements that arose from evaluation exercises are provided in Figures 4 and 5 for UBCSAND (Beaty and Byrne 2011) and PM4Sand (Ziotopoulou and Boulanger 2016), respectively. These figures summarize the results of single element simulations of undrained DSS loading with a range of initial static shear stress ratios (α). Results are presented as a K_α ratio, which is the CRR divided by the CRR for $\alpha = 0$. The results shown for UBCSAND 904a in Figure 4a are dramatically different from experimental trends in the literature (e.g., Boulanger 2003), which led to the development of UBCSAND 904aR with its improved approximation of experimental trends in Figure 4b (Beaty and Byrne 2011). The results for PM4Sand version 2 in Figure 5a were insensitive to α, which also motivated the development of version 3 with its improved approximation of experimental trends in Figure 5b. The limitations in the earlier versions of both constitutive models were immediately evident upon their comparisons to empirical relationships, did not require soil-specific laboratory testing to identify, and were not stress-strain behaviors that could be fixed by calibration (i.e., the limitations were inherent to the model formulations). Similar comparisons of constitutive models against empirical data for the effects of overburden stress, number of uniform loading cycles, irregular cyclic loading, and post-triggering reconsolidation (e.g., Ziotopoulou and Boulanger 2012, 2013, 2016, Ziotopoulou et al. 2014) have proven useful for identifying limitations and biases in model behaviors and promoting improvements.

Evaluation or validation of an NDA modeling procedure, with its specific constitutive models or calibration protocols, is a process that improves as the number of analyzed case histories and physical model data sets increases. Multiple evaluation studies are necessary because the accuracy of an NDA procedure is both system- and loading-dependent, with the soil properties that control the system response differing with the system configuration and the imposed loading. For example, the responses of embankment dams, waterfront structures, underground structures, and level sites (Figure 6) each involve different overburden stresses, initial shear stresses, and shearing modes, and the sensitivity of their responses to the CRR, cyclic mobility, and residual strength all depend on the seismic loading characteristics. For this reason, good agreement between simulated and measured responses for one case history or physical model test does not ensure good agreement for any other system or for the same system under a different loading. The accumulation of experience from multiple evaluation studies also provides a basis for quantifying potential biases and dispersion levels in model predictions, while also helping to identify areas where the NDA modeling procedures can be improved.

CONSTITUTIVE MODEL COMPARISONS AND IMPROVEMENTS

Comparisons of NDA results obtained using different constitutive models can provide a sense of modeling uncertainty for any specific structure and can promote progressive improvements in the models and their calibration protocols. If the results of NDAs using two or more constitutive models are reasonably consistent, the outcome is usually an increased confidence in the reasonableness of the range of estimated performance. If the NDA results are instead dramatically different, the outcome is usually a reduced confidence in any of the modeling results until the root cause for the difference has been identified. The latter situation provides opportunities to identify specific limitations in the constitutive models or the ways they are used, which in turn provides important feedback to the model developers.

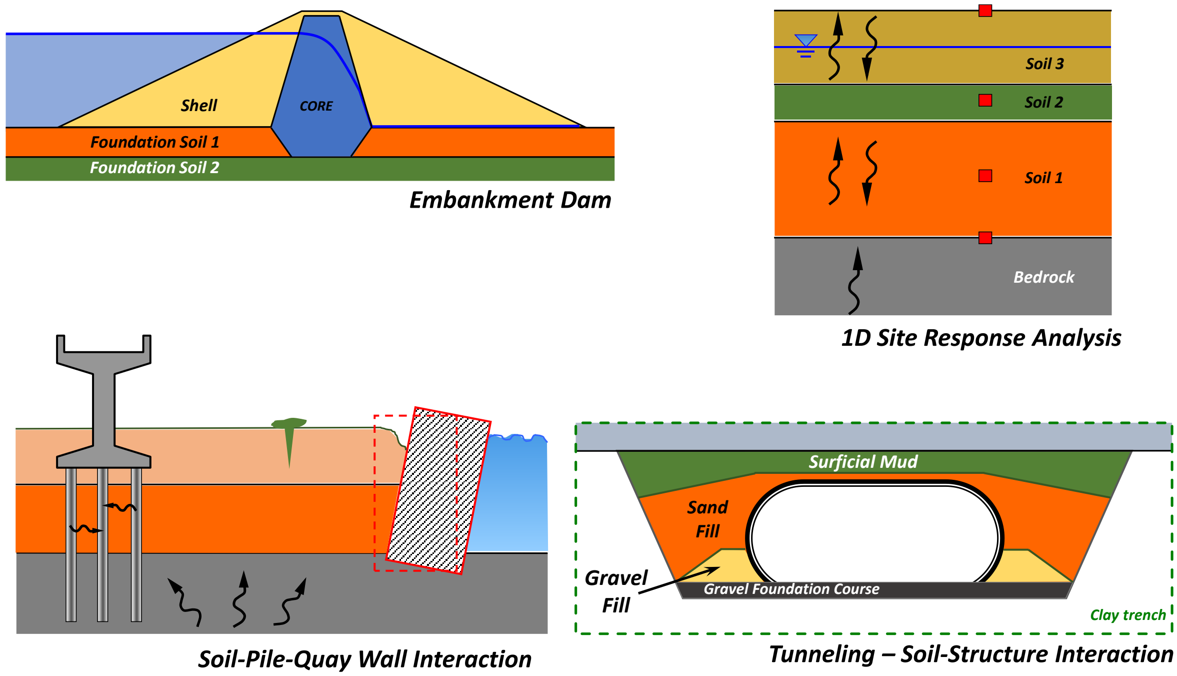

Figure 6. Examples of systems that may be controlled by different aspects of liquefaction behaviors, such that validation of NDA procedures is generally problem specific.

NDA Comparisons with Reasonably Consistent Results

Results of two NDA studies that obtained reasonably consistent results using two or more constitutive models for the liquefiable soils are illustrated in Figures 7 and 8. The first study was for an embankment dam with liquefiable alluvium beneath its downstream shell (Hadidi et al. 2017). The deformations computed for one of the considered input motions are shown in Figure 7 (Hadidi 2017, personal communication) for the alluvium modeled using three different constitutive models: (a) a Mohr Coulomb-based cycle counting model, (b) the PM4Sand version 3 model, and (c) the UBCSAND 904aR model. The Mohr Coulomb-based cycle counting model can only provide a first order accounting of the effects of liquefaction triggering and strength loss on embankment deformations, as it does not approximate any other key stress-strain behaviors like cyclic mobility. The other two models provide more realistic simulations of stress-strain behavior including cyclic mobility. The three models were calibrated to similar CRR values across a range of overburden stresses and assigned the same post-triggering S_r values. The three models produced different extents of liquefaction triggering beneath the downstream shell, but the overall patterns of response and deformation were similar. The final displacements for the analysis case shown in Figure 7 (i.e., the vector sum of the horizontal and vertical components) ranged from 0.4-1.1 m at the crest, 0.3-1.4 m at the middle of the downstream face, and 1.0-1.6 m near the downstream toe.

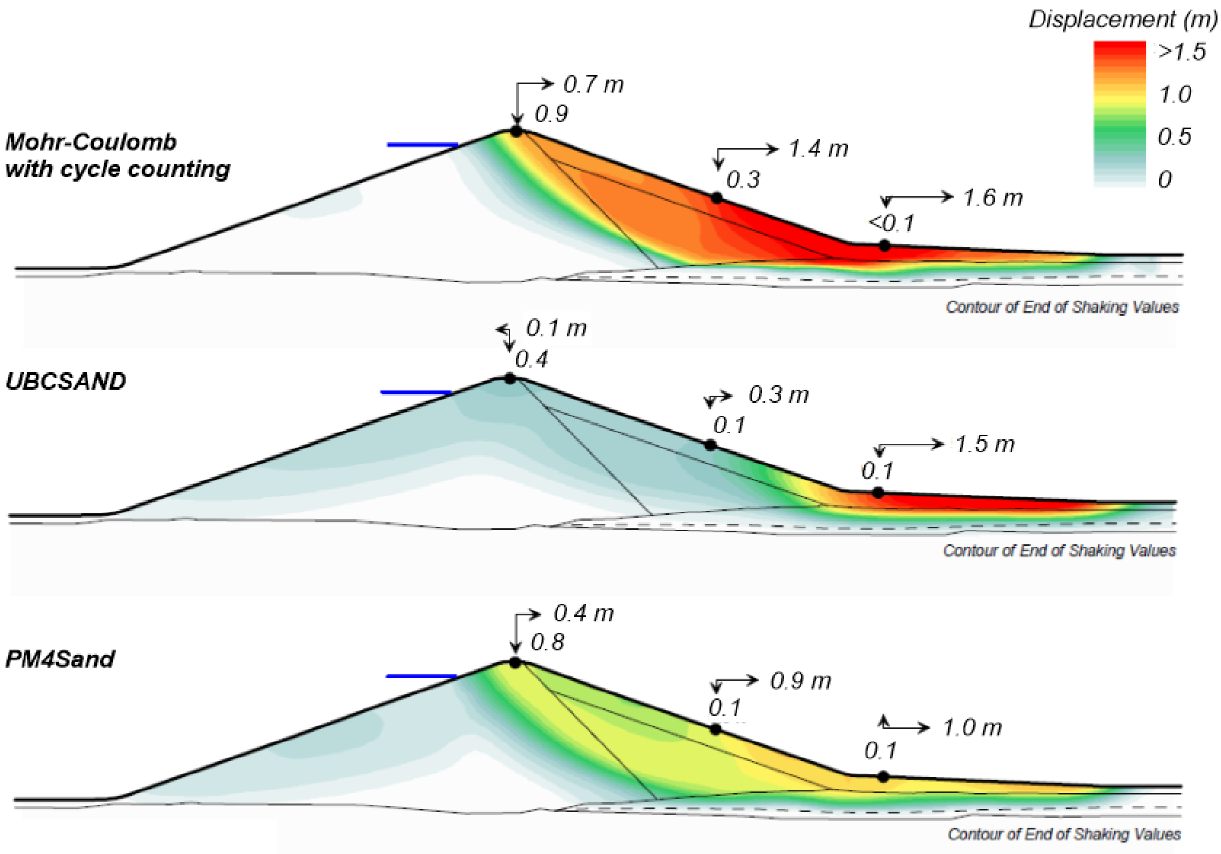

Figure 7. Comparison of deformations for a dam using thee different models for the liquefiable alluvium under the downstream shell (Hadidi 2017, pers. comm.).

These computed displacements are reasonably consistent, given that they reinforce the overall assessment of expected performance for this level of loading.

The second study illustrated in Figure 8 (Montgomery and Abbaszadeh 2017) was also for an embankment dam but with liquefiable alluvium under both the upstream and downstream shells. The NDAs were repeated using the UBCSAND 904aR and PM4Sand version 3 models for cases with the shells assigned $(N_1)_{60cs}$ values of 25 or 35, the alluvium assigned $(N_1)_{60cs}$ of 10, 15, or 20 and with 3 different input motions scaled to peak outcrop accelerations of 0.5 or 0.75g. Montgomery and Abbaszadeh (2017) compare the crest and shell displacements for individual cases and observed reasonable overall agreement between results obtained using the two models, although the PM4Sand analyses tended to give larger displacements when the alluvium had the higher blow counts and the UBCAND analyses tended to give the larger displacements when the alluvium had the lower blow counts. The results of all their analysis cases are summarized in Figure 8b, illustrating the above trends for different alluvium properties. These analyses were

(a)

(b)

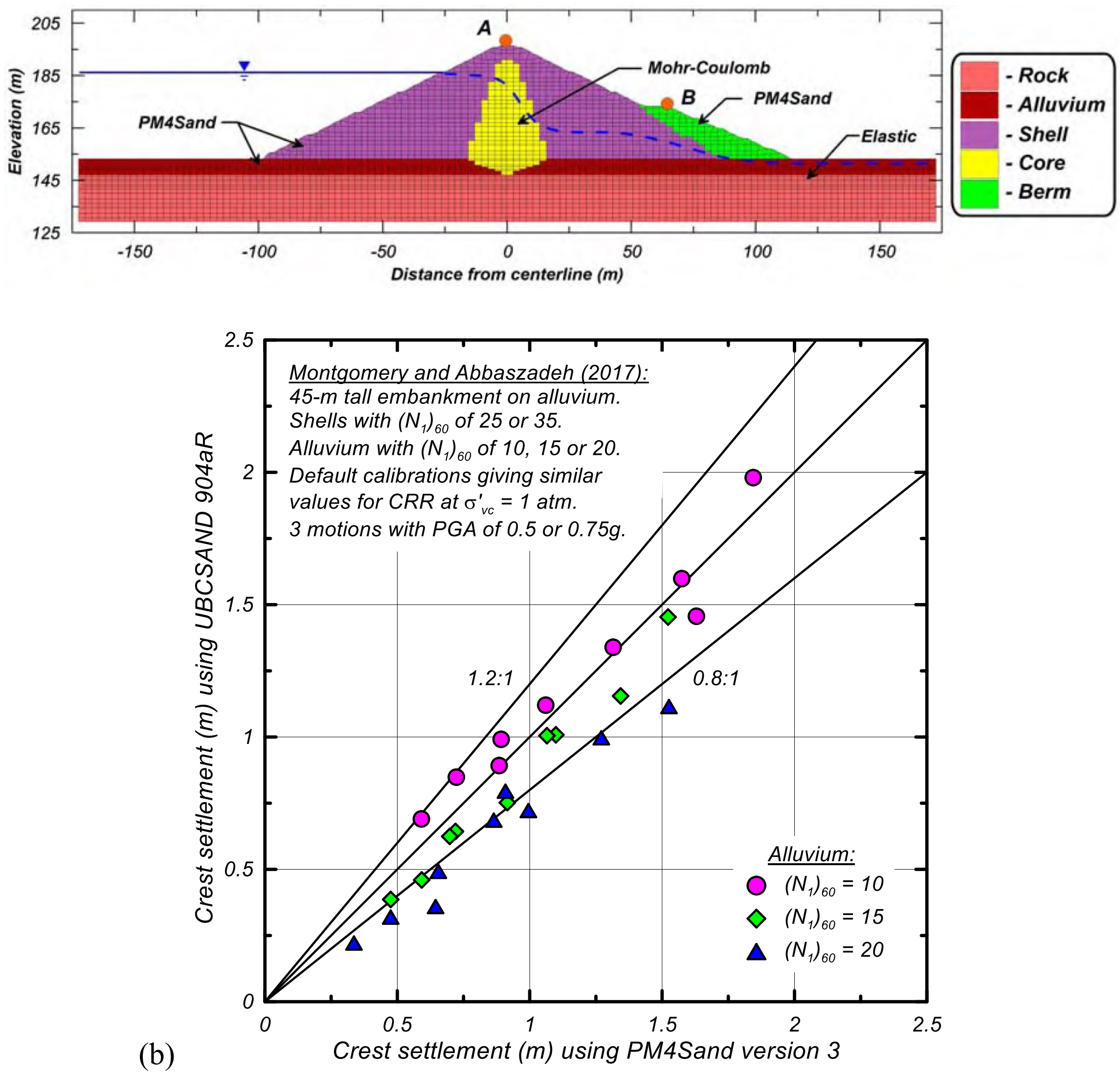

Figure 8. Comparison of NDA results: (a) embankment on alluvium, and (b) crest settlements computed using UBCSAND and PM4Sand (results from Montgomery and Abbaszadeh 2017).

based on the default calibrations provided by the model developers, which results in similar CRR values at an overburden stress of about 1 atm. Thus the differences in responses shown in Figure 8 reflect differences in simulated strengths and stress-strain behaviors for other overburden stresses, which the authors noted could have been accounted for by calibrating the models to the same CRR over smaller intervals of overburden stress.

Other comparative studies have been performed using the above constitutive models with similar or different calibration protocols, and found different magnitudes of differences and dependencies (e.g., Armstrong et al. 2013, Armstrong and Boulanger 2015). Thus, the results of any comparative study must be expressed as conditional on the calibration procedures, and cannot be generalized to other project configurations, loading conditions, or user practices.

An NDA Comparison with Inconsistent Results

Larger differences between NDA results using two or more constitutive models can be indicative of more serious limitations in the constitutive models, calibration procedures, or numerical modeling procedures. For example, some recent NDA studies using UBCSAND 904aR and PM4Sand version 3 found that the NDAs using UBCSAND predicted liquefaction triggering to greater depths with ground displacements that were several times those obtained using PM4Sand. Common features of the systems being analyzed were larger-than-typical depths of liquefiable soils, gently sloping ground, and long-duration subduction zone motions. Detailed examination of response time series showed that significant amounts of pore pressure generation and ground displacement with the UBCSAND model were developing during relatively low-levels of shaking over long durations. For example, the acceleration time series shown in Figure 9 is illustrative of how a subduction zone event can produce large numbers of low-level loading cycles both before and after the interval of strongest shaking. The root cause of the differences in NDA responses under these types of loading conditions were further investigated using single element simulations, as described below.

The two models were first calibrated to an equivalent CRR of 0.094 for 15 uniform loading cycles to cause 3% shear strain for an initial σ'_{vc} of 400 kPa and an initial static shear stress ratio ($\alpha = \tau_{hv}/\sigma'_{vc}$) of 0.02. For UBCSAND 904aR, the calibration corresponds to the default properties generated by the model for an $(N_1)_{60cs}$ of 15. For PM4Sand, the calibration corresponds to an initial D_R of 55%, modulus coefficient G_o of 677, contraction rate parameter h_{po} of 0.15, and default values for all other parameters. The calibrated models produced reasonably consistent responses in terms of CRR versus number of uniform loading cycles, as shown in Figure 10. For both models, CSRs of 0.04 or less would require thousands of loading cycles to trigger liquefaction. The stress-strain responses of the two models at a CSR of 0.094, as compared in Figure 11, show shear strains accumulating in the direction of the static shear bias at rates of about 1.5%/cycle for UBCSAND and 2.8%/cycle for PM4Sand. The greater rate of strain accumulation for PM4Sand suggests that these differences in cyclic mobility behavior are not the reason UBCSAND produced larger displacements at the system level.

One set of single-element simulations was then used to examine differences in pore pressure generation for the two constitutive models under low-level CSRs for two different loading scenarios. In the first scenario, the pore pressure generation responses were checked by subjecting them to 100 uniform cycles at CSRs of 0.015, 0.02, and 0.025. These low-level CSRs produced almost no excess pore pressure in the UBCSAND model (Figure 12a), but did produce excess pore pressure ratios (r_u) that stabilized at values of about 20% in the PM4Sand model (Figure 12b). These low r_u values are consistent with the fact it would take thousands of cycles to trigger

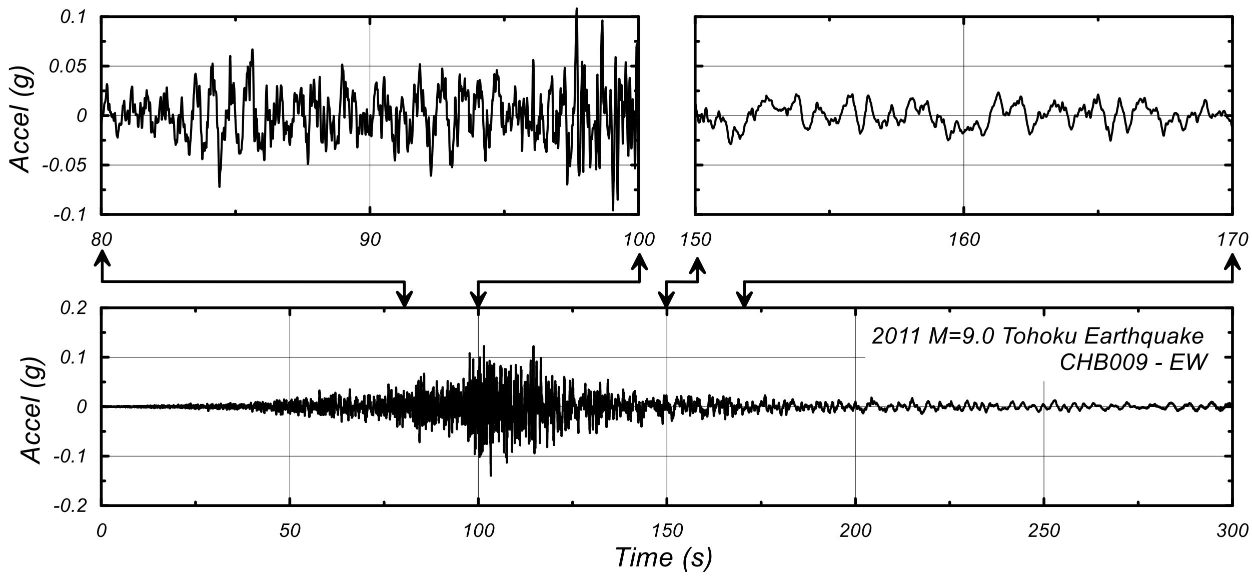

Figure 9. Example of long duration motion with large number of low-level cycles.

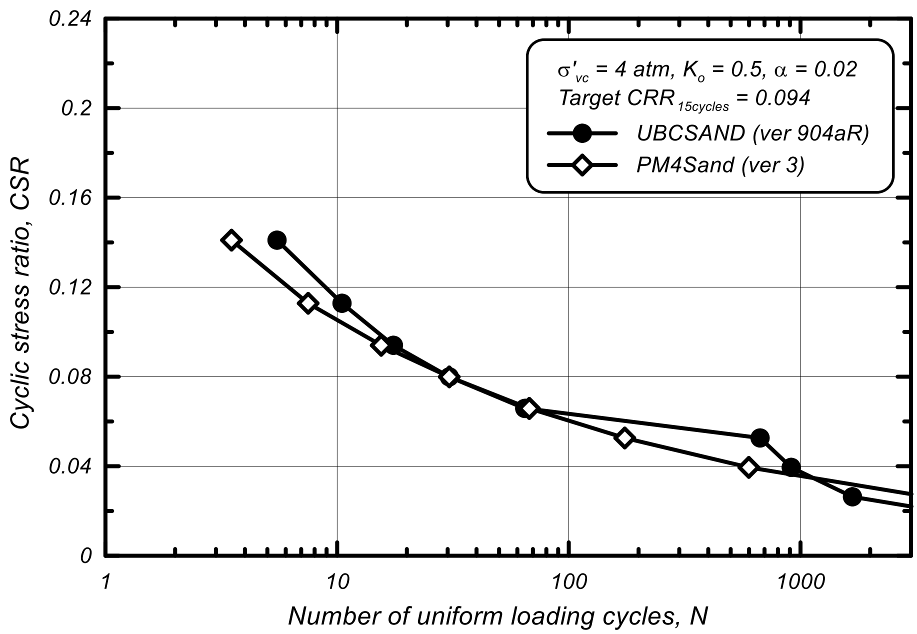

Figure 10. CSR versus number of uniform loading cycles to cause 3% shear strain in undrained simple shear for PM4Sand and UBCSAND.

liquefaction in either model (Figure 10). In the second scenario, the elements were first subjected to a uniform CSR of 0.12 until r_u reached about 30% (3-4 cycles of loading), after which the CSR was reduced to 0.015, 0.02, or 0.025. For the UBCSAND model, the uniform CSR of 0.02 triggered liquefaction after only 65 loading cycles, whereas the CSRs of 0.015 and 0.025 resulted in significant increases in r_u but did not trigger liquefaction within the next 100 cycles. For the

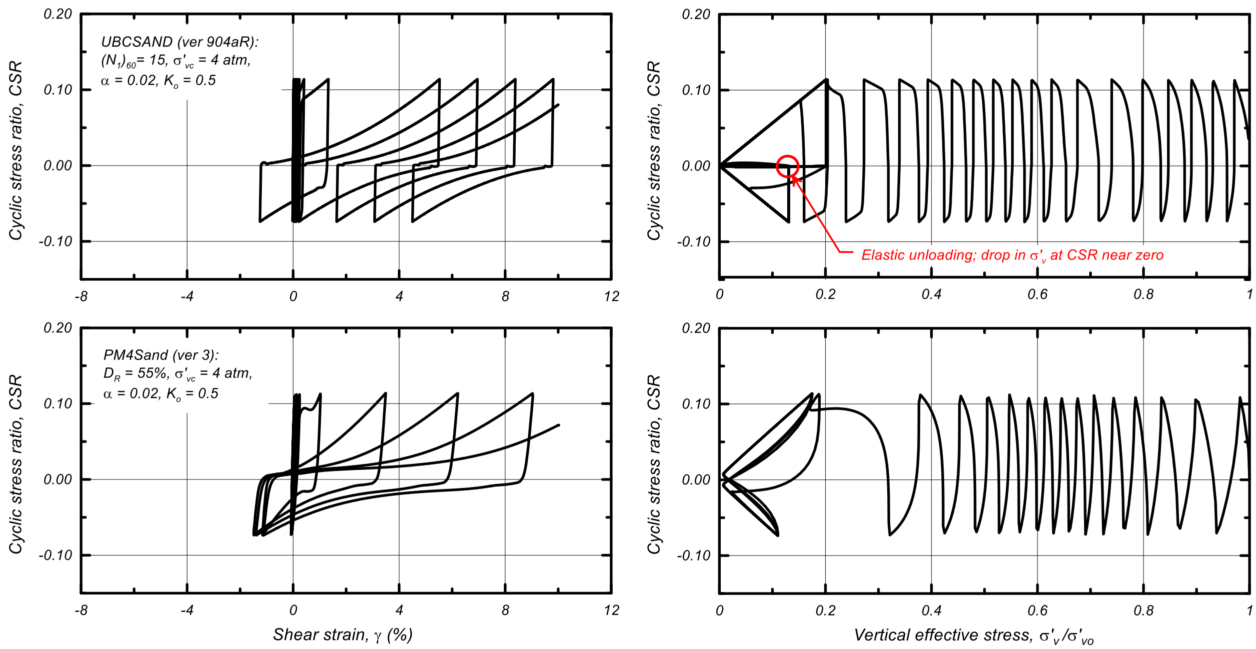

Figure 11. Stress-strain and stress path responses from single-element simulations of uniform cyclic loading in undrained simple shear with an initial static shear stress ratio of 0.02 using UBCSAND (upper plots) and PM4Sand (lower plots).

PM4Sand model, the uniform CSR of 0.015, 0.02, or 0.025 increased r_u by only a few percent over the next 100 cycles. The rates of pore pressure generation in UBCSAND at these low CSR levels are inconsistent with the calibrated CRR curves (Figure 10), given that it should still have taken hundreds or thousands of cycles to raise the r_u from 30% to 100%. Furthermore, the much greater rate of pore pressure generation at a CSR of 0.02 compared to CSRs of 0.015 or 0.025 is indicative of a model limitation or coding problem. These differences in single element responses are consistent with the system level NDAs showing that UBCAND generated sufficient pore pressure during low-level loading to trigger more extensive liquefaction during long-duration subduction zone motions.

A second set of single-element simulations was used to examine differences in shear strain accumulation after a r_u of 100% was triggered. The elements were first subjected to a uniform CSR of 0.12 until a shear strain of 3% developed, after which another 20 loading cycles at a CSR of 0.015, 0.02, or 0.025 were applied. For the UBCSAND model, these low-level CSRs caused shear strains to reach values of 70-100%, corresponding to a strain accumulation rate of 3.5-5.0% per cycle (Figure 13a). This rate of strain accumulation is illogically 2-3 times greater than produced under the much stronger loading used during model calibration (Figure 11). For the PM4Sand model, the same low-level CSR caused shear strains to reach values of 20-30%, or about 0.6-1.0% per cycle (Figure 13b). This rate of strain accumulation is more reasonably a quarter to a third of that produced under the stronger loading used during model calibration (Figure 11). These differences in strain accumulation rates at low-level CSRs are consistent with the system level

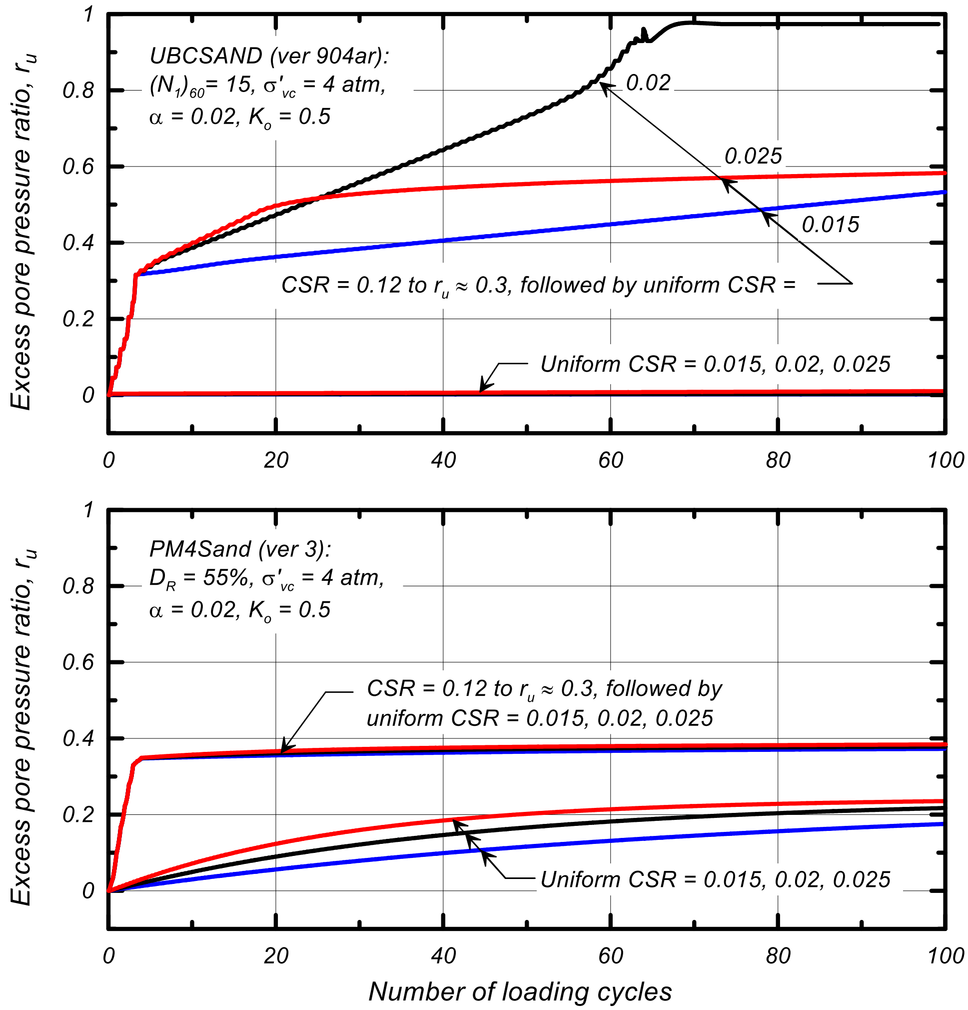

Figure 12. Pore pressure generation in undrained DSS for uniform low-level CSR of 0.015, 0.02, or 0.025, or the combination of CSR = 0.12 to reach r_u = 0.3 followed by uniform low-level CSR of 0.015, 0.02, or 0.025: (a) UBCSAND, and (b) PM4Sand.

responses with UBCSAND having produced several times greater rates of deformation during long-duration low-level shaking after the period of strongest shaking had passed.

The above responses of UBCSAND 904aR, with its overly rapid pore pressure generation and post-triggering strain accumulation rates at low CSRs, are unusual stress-strain behaviors that will require model revisions to correct. Tsuboi et al. (2015) evaluated a different elasto-plastic constitutive model and showed that it also overestimated deformations in liquefiable soils during low-level long-duration cyclic loading when calibrated by conventional procedures. Laboratory test data for irregular, long-duration loading conditions are relatively limited, but the existing data are sufficient for providing some bounds on reasonable behaviors (e.g., Tsuboi et al. 2015, Ziotopoulou and Boulanger 2016). Additional laboratory tests that approximate a wider range of irregular, long-duration loading conditions are needed for guiding refinements of these and other constitutive models. The problematic stress-strain behaviors discussed herein appear to manifest

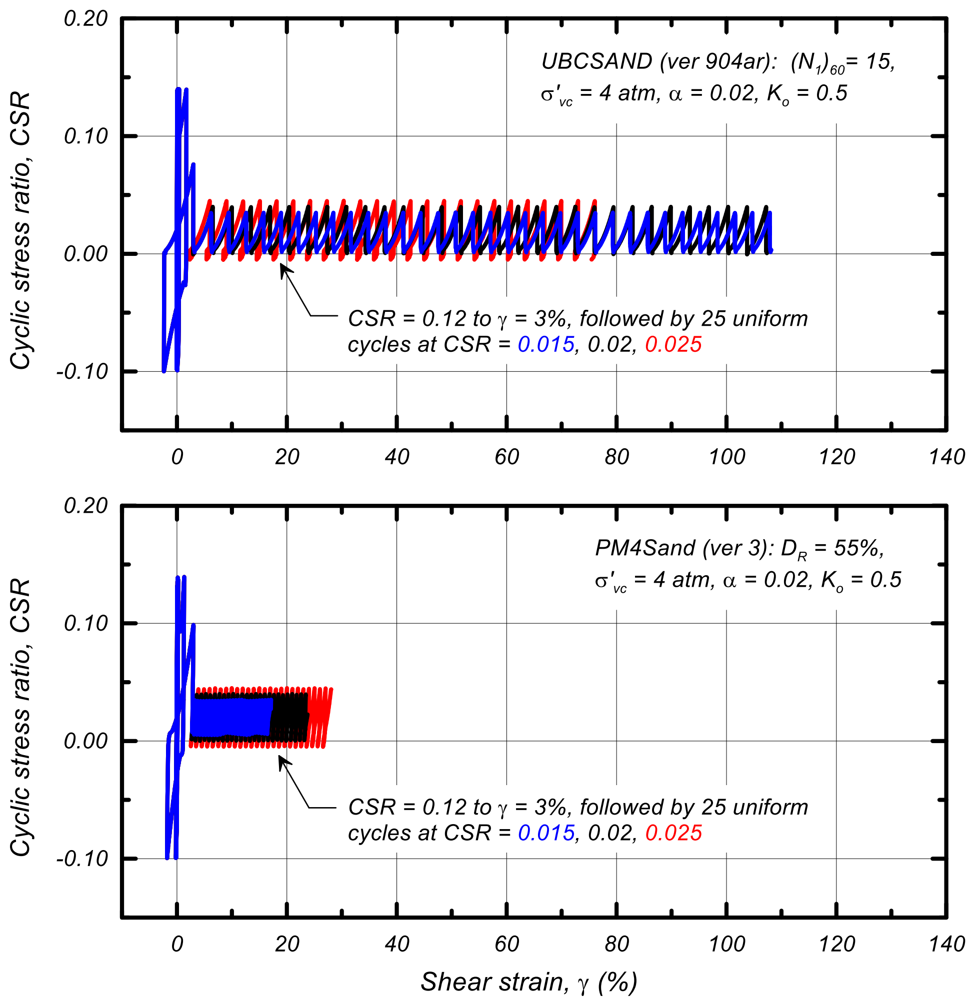

Figure 13. Stress-strain respones in undrained simple shear for 25 uniform low-level cycles at CSR of 0.015, 0.02, or 0.025 after 5-6 cycles at CSR = 0.12 produced 3% shear strain: (a) UBCSAND, and (b) PM4Sand.

themselves most strongly for the conditions of small initial static shear stress ratios at higher overburden stresses, and thus have not been observed or apparent in NDA studies involving steeper ground conditions, smaller overburden stresses, or shorter duration motions.

The preceding example illustrates how the combination of system and single-element simulations can be used to isolate and identify potential limitations in constitutive models and thus promote the improvement of those models. For this specific example, the limitations in UBCSAND 904aR identified by the above exercise are expected to be addressed in the near future. Other cases of poor agreement between NDA results using two or more models have identified calibration protocols or numerical modeling procedures as the source of the differences; e.g., differences in the criteria used to assign residual shear strengths in the post-shaking stability analyses and differences in whether undrained shear strengths are allowed to exceed preearthquake drained strengths or not, have both been causes of poor agreement on past projects (e.g., Boulanger et al. 2015). In either situation, the challenge is that systems produce a myriad of loading paths that are beyond those covered in most calibration protocols, and problems with unrealistic constitutive model responses often require detailed examination of the elemental responses within the system level analyses supplemented by single element simulations to isolate the problematic behavior. When major limitations in a constitutive model or modeling procedure are identified, it is important that the findings be shared and the use of that model or modeling procedure put on hold for related applications until the problem is corrected or remedied.

REVIEW AND DOCUMENTATION PRACTICES

The utility of an NDA study depends on clear and thorough documentation, since it provides the basis for effective internal and external review processes, a means for promoting consistent or best practices, and value to the owner or client in the event that the project's seismic performance is reexamined in the future. Review processes can enable multiple parties to contribute to finding errors, ensuring best practices are adhered to, and extracting insights and benefits. For analyses that use two or more models, the ability to resolve or understand any systematic or unusual difference in results depends on the documentation.

Recommendations regarding NDA documentation practices, from the perspective of a reviewer, are provided in Boulanger and Beaty (2016). Their recommendations draw from best practices in industry and are grouped around twelve key aspects. These twelve aspects are listed in Table 1 along with examples of the types of questions or details that should be addressed in the documentation. Aspects 1 and 2 pertain to awareness of the potential failure modes and important behaviors for the system being studied, and the evaluation/validation record for the NDA modeling procedures. Aspects 3 (site characterization) and 6 (input ground motions) pertain to the basis for defining the model geometry, properties and imposed loading. Aspects 4 and 5 pertain to the constitutive model calibration and numerical modeling procedures. Aspects 7-10 pertain to initial static stress, dynamic response, post-shaking stability, and sensitivity analyses. Aspects 11 and 12 pertain to awareness of the uncertainties in the NDA modeling results and the reasonableness of the overall conclusions drawn from the NDA study.

The process of addressing the aspects listed in Table 1 and the associated set of questions listed in Boulanger and Beaty (2016) is likely to be iterative like the NDA process itself. NDA studies frequently benefit from a cycle of updates or refinements to the input parameters based on the insights gained as the study progresses. For example, the results of the initial analyses may indicate that certain parameters have a greater influence on the computed response than originally anticipated, such that additional effort to refine the estimates of those parameters is warranted. In fact, addressing these questions as the NDA study progresses can help identify when such a cycle of refinement may or may not be warranted. Thus, the order of the questions in Table 1 should not be viewed as implying a linear process for either the NDA study or its review.

Table 1: Key aspects and illustrative questions for reviewing a nonlinear dynamic analysis study (abbreviated from Boulanger and Beaty 2016)

Key aspect and illustrative questions for the review process
Aspect 1: Seismic failure modes and important behaviors • Have the potential failure modes or performance objectives been summarized or discussed? • Have the soil properties and stress-strain behaviors important to those failure modes been identified? • Are limitations in the NDA model's ability to simulate any key soil properties or system behaviors acknowledged?
Aspect 2: Validation record for the numerical modeling procedure • Have the constitutive models, calibration processes, and numerical modeling procedures been evaluated/validated for systems similar to the one under investigation? • How well do the constitutive models reproduce, in single element loading simulations, stress-strain responses consistent with empirical data across the loading conditions of interest?
Aspect 3: Site characterization basis for material properties • Has the basis for all material parameters been described and related to the site characterization? • Would additional explorations or testing be likely to significantly change the site characterization?
Aspect 4: Calibration and evaluation of the constitutive model • Are all constitutive input parameters listed? • Are constitutive model responses from single element simulations shown for the key properties of interest under representative initial stress and loading conditions?
Aspect 5: Numerical modeling procedures • Have the modeling approaches for the static, dynamic, and post-shaking phases of the analyses been fully documented and are the approaches reasonable?
Aspect 6: Input ground motions • Are the selected ground motions consistent with the seismic hazard and the numerical model? • Are the significant characteristics of the motions fully described? • Are the motions being applied to the model in an appropriate manner?
Aspect 7: Initial static stress conditions • Are the initial static stress states reasonable, including the distributions for vertical stresses (evidence of arching), K_o and α? • Are initial pore pressures consistent with available piezometer data?
Aspect 8: Dynamic response • Is the simulated dynamic response reasonable, and is it presented in sufficient detail to allow for this assessment? Documentation for at least one analysis case should include acceleration and displacement time series and response spectra for key points, stress paths and stress-strain responses for representative elements, and deformed shapes with contours of strain, pore pressure ratio, and displacement. • Has the model been evaluated against field observations or recordings from past earthquakes?
Aspect 9: Post-shaking deformations • Is the post-dynamic stability analysis reasonable, and has it been sufficiently documented (for at least one motion) to permit this assessment? • How have post-earthquake strengths been modeled in the analyses, allowing for rate effects, cyclic degradation or remolding, dilation, cracking, void redistribution, or other processes?
Aspect 10: Parametric analyses • Have sufficient parametric analyses been performed to identify the soil properties, system characteristics, procedural issues, or other parameters most affecting the computed responses?

Aspect 11: Uncertainties and limitations • Have the primary uncertainties and limitations in the NDA model (e.g. cracking) been identified and discussed? • Has there been any overall tendency for overly optimistic or pessimistic selection of inputs at each step of the process?
Aspect 12: Reasonableness of conclusions • Has the case been made, in plain language, for the conclusions and recommendations drawn from the NDAs, with due consideration for the geology, material characteristics, system configuration, seismic hazard, estimated response, potential consequences, and key sources of uncertainty? • Has the potential for additional information (e.g., explorations or analyses) to change the conclusions or recommendations been adequately discussed?

Addressing these review questions adds significant value and does not involve significant engineering effort for most well-executed NDA studies. In most cases, the effort involves brief statements documenting what was done and presenting intermediate results that were likely already available. The effort required to document these details can be minimized if the need for transparent documentation is established at the start of the study. In many situations, inadequate documentation can impede reviews by regulatory agencies or review boards, leading to additional cycles of reviews and responses, or to delayed identification of an error or problem that necessitates repeating the analyses. In those situations, inadequate documentation early in the NDA study can lead to increased overall costs.

Delivery of a quality NDA study requires a team with a high degree of technical expertise and sufficient time and resources to perform the work. In some situations, the technical team may have an individual whose expertise is numerical modeling, while other team members provide the expertise on site characterization, seismic hazard characterization, or the damage/loss/decision aspects of the study (Figure 1). In any situation, there are strong advantages to ensuring that the numerical analyst is well familiarized with the other aspects of the NDA study so they understand the basis for the analysis inputs (e.g., stratigraphy, properties, loading) and the intended use of the analysis results (e.g., potential failure modes, performance criteria). Similarly, it is important for quality assurance that the team include a reviewer or supervisor with sufficient technical expertise in numerical modeling to check the details of the analyst's work or provide guidance as appropriate.

CONCLUSIONS

Three aspects of NDA practices that are important for evaluating the seismic performance of geotechnical structures affected by liquefaction or cyclic softening were discussed: (1) selection and calibration of constitutive models, (2) comparison of NDA results using two or more constitutive models, and (3) documentation.

The quality and utility of NDAs for evaluating liquefaction effects depend strongly on the selection, calibration, and limitations of the constitutive models. Confidence in the NDA results depends on documenting the degree to which the selected constitutive models can simulate the soil properties and stress-strain behaviors important to the system being analyzed. Single element simulations that evaluate constitutive responses against empirical data over a broad range of loading conditions are an essential part of that process and should be expected in practice.

Comparisons of NDA results using two or more constitutive models are valuable for: (1) evaluating modeling uncertainty for any specific structure, provided the NDA results are reasonably consistent, and (2) promoting progressive improvements in the models and their calibration protocols when the NDA results are not reasonably consistent. An example was presented where poor agreement in NDA results identified a potential problem, after which single element simulations were able to identify the problematic constitutive responses, and thus help guide further improvements in one of the constitutive models.

The utility of an NDA study is strongly dependent on the clarity and thoroughness of the documentation, since it provides the basis for effective internal and external reviews, advancing best practices, and future reexaminations of seismic performance. Sufficiently comprehensive documentation should be an expectation in practice.

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REFERENCES

Armstrong, R. J., Boulanger, R. W., and Beaty, M. H. (2013). "Liquefaction effects on piled bridge abutments: Centrifuge tests and numerical analyses." Journal of Geotechnical and Geoenvironmental Engineering, ASCE, 139(3), 433-443.

Armstrong, R. J., and Boulanger, R. W. (2015). "Numerical simulations of liquefaction effects on piled bridge abutments." 6^{th} International Conference on Earthquake Geotechnical Engineering, November 1-4, Christchurch, New Zealand.

Beaty, M. H., and Byrne, P. M. (2011). UBCSAND constitutive model: version 904aR. Documentation report: UBCSAND constitutive model on Itasca UDM Web Site, February.

Beaty, M. H., and Perlea, V. G. (2011). Several Observations on Advanced Analyses with Liquefiable Materials. In Proc., 31st USSD Annual Meeting and Conference, United States Society on Dams, San Diego, April 11 – 15, 2011. (pp. 1369-1397).

Boulanger, R. W. (2003). "Relating K_α to relative state parameter index." Journal of Geotechnical and Geoenvironmental Engineering, ASCE, 129(8), 770-773.

Boulanger, R. W., and Beaty, M. H. (2016). "Seismic deformation analyses of embankment dams: A reviewer's checklist." Proceedings, Celebrating the Value of Dams and Levees – Yesterday, Today and Tomorrow, 36th USSD Annual Meeting and Conference, United States Society on Dams, Denver, CO, 535-546

Boulanger, R. W., and Ziotopoulou, K. (2015). "PM4Sand (Version 3): A sand plasticity model for earthquake engineering applications." Report No. UCD/CGM-15/01, Center for Geotechnical Modeling, Department of Civil and Environmental Engineering, University of California, Davis, CA, 112 pp.

Boulanger, R. W., Montgomery, J., and Ziotopoulou, K. (2015). "Nonlinear deformation analyses of liquefaction effects on embankment dams." Perspectives on Earthquake Geotechnical Engineering, A. Ansal and M. Sakr, eds., Geotechnical, Geological and Earthquake Engineering 37, 247-283, Springer, DOI 10.1007/978-3-319-10786-8_10.

Boulanger, R. W., Kamai, R., and Ziotopoulou, K. (2014). "Liquefaction induced strength loss and deformation: Simulation and design." Bulletin of Earthquake Engineering, Springer, 12: 1107-1128, 10.1007/s10518-013-9549-x.

Dawson, E. M., Roth, W. H., Nesarajah, S., Bureau, G., and Davis, C. A. (2001). "A practice oriented pore pressure generation model." Proceedings, 2nd FLAC Symposium on Numerical Modeling in Geomechanics. Oct. 29-31, Lyon, France.

Hadidi, R., Dinsick, A., Wahl, D., Hu, J., and Perez, A. (2017). "Characterization and seismic performance of Bouquet Canyon Dam No. 1." Proc., Performance-based Design in Earthquake Geotechnical Engineering, PBD-III Vancouver, M. Taiebat et al., eds., ISSMGE Technical Committee TC203, paper 110.

Montgomery, J., and Abbaszadeh, S. (2017). "Comparison of two constitutive models for simulating the effects of liquefaction on embankment dams." Proceedings, 37th Annual USSD Conference, USSD, Denver, CO.

Montgomery, J., and Boulanger, R. W. (2016). "Effects of spatial variability on liquefaction-induced settlement and lateral spreading." Journal of Geotechnical and Geoenvironmental Engineering, ASCE, 2017, 143(1), 04016086, 10.1061/(ASCE)GT.1943-5606.0001584.

Naesgaard, E., and Byrne, P. M. (2007). "Flow liquefaction simulation using a combined effective stress total stress model." Proceedings Ottawa 2007, Canadian Geotechnical Society, paper 577.

Tsuboi, S., Ohsumi, T., Uzuoka, R., and Sento, N. (2015). "Applicability of effective stress analysis for prediction of deformation during strong motion with long duration." Computer Methods and Recent Advances in Geomechanics, Oka, Murakami, Uzuoka, and Kimoto (eds), Taylor and Francis Group, 683-686, ISBN 978-1-138-00148-0.

Ziotopoulou, K., and Boulanger, R. W. (2012). "Constitutive modeling of duration and overburden effects in liquefaction evaluations." 2nd International Conference on Performance-Based

Design in Earthquake Geotechnical Engineering, ISSMGE, Taormina, Italy, May 28-30, paper no. 03.10, 467-482.

Ziotopoulou, K., and Boulanger, R. W. (2013). "Numerical modeling issues in predicting post-liquefaction reconsolidation strains and settlements." 10th International Conference on Urban Earthquake Engineering, March 1-2, Tokyo Institute of Technology, Tokyo, Japan, 469-475.

Ziotopoulou, K., and Boulanger, R. W. (2016). "Plasticity modeling of liquefaction effects under sloping ground and irregular cyclic loading conditions." Soil Dynamics and Earthquake Engineering, 84 (2016), 269-283, 10.1016/j.soildyn.2016.02.013

Ziotopoulou, K., Maharjan, M., Boulanger, R. W., Beaty, M. H., Armstrong, R. J., and Takahashi, A. (2014). "Constitutive modeling of liquefaction effects in sloping ground." Tenth U.S. National Conference on Earthquake Engineering, Frontiers of Earthquake Engineering, July 21-25, Anchorage Alaska.