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Automatic calibration of the SANISAND parameters for a granular material using multi-objective optimization strategies

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ABSTRACT: The parameter calibration of a constitutive model is a requisite to counter the uncertainty in the parameters and to approximate the simulation results effectively. Yielding a robust set of parameters for various test conditions is complicated as innumerable parameter combinations have to be investigated. In previous works, this calibration has been performed manually by trial and error without checking the robustness of the chosen parameters. Therefore, the present study introduces an automated calibration procedure using multi-objective optimization techniques. This assists in searching the parameter domain space extensively for better combinations that simulate the experiment results precisely. Though this approach is quite popular in various other engineering aspects, proposing the concept of calibrating the soil parameters and validating their efficiency has been always a challenge and interesting in this framework. In this research, SANISAND model parameters have been calibrated for crushed glass material under different triaxial conditions considering the barotropy, and pycnotropy effects. The results demonstrated that the optimized SANISAND parameters approximated the experiment results far better than manually calibrated results. This calibration approach facilitates in conserving the robust parameters besides dealing with time constraints and motivates the idea of adapting this automation platform to any constitutive model for significant approximations.

Keywords: Automatic calibration; SANISAND model; Granular materials; Multi-objective optimization; NSGA-III.

1 INTRODUCTION

Different constitutive models have been developed to describe soil behaviour more accurately and quite a few advanced models, such as SANISAND, hypoplasticity, etc, have been extensively implemented and analysed. In each of these models, robust parameter calibration is a difficult task in which a combination of constitutive parameters has to be chosen that approximate numerous experimental results under different test conditions. This can be done manually in an iterative manner to quantify the experimental data and the simulation data discrepancy. But, this approach needs a high degree of experience. Besides, it is time-consuming to achieve a competent set that reproduces barotropic (pressure dependency) and pycnotropic (relative density) test conditions without investigating the parameter space entirely, which would demand countless combinations.

On the other hand, an automated calibration can be handy in testing various parameter sets to obtain the robust one. This concept has already been in practice in many studies, e.g. Knabe et al. (2012), Vallurupalli (2020), etc. However, all the mentioned works incorporated available test data in their calibration, and the resultant parameter set was decided without validation. Hence, the resulting parameter set may not represent the best constitutive behaviour for other test conditions. Therefore, in this study, specific test data have been chosen for calibration and the attained parameters have been thoroughly validated with respect to additional test data for its stability and robustness. One such approach for validating the numerical model can be seen in Zhao et al., (2015). The automatic calibration in this research is based on multi-objective optimization strategies. Multi-objective optimization can be defined as the process in which a function with many objectives can be optimized (either minimized or maximized) with certain algorithms like genetic algorithms (GA), particle swarm optimization, etc. GA-based strategies have been chosen for this work as they can handle multiple objectives. Different types of these genetic algorithms and their implementations can be found in seminal works like Painton et al. (1995), Popov (2005), Wright (1991), etc. Non-dominated sorting genetic algorithm-III (NSGA-III) introduced by Deb and Jain (2013) has been considered the optimizing algorithm in this calibration for deriving the optimal set of constitutive model parameters. A graphical convergence comparison has been performed among the different optimization methods on standard test functions (Deb et al., 2006) and NSGA-III has been preferred for this research for its efficiency.

The simple plasticity sand model accounting for the fabric change effect developed by Dafalias and Manzari (2004), the precursor of the family of models known today as SANISAND (Simple ANIsotropic SAND model) is used in this research. For the sake of simplicity, Dafalias and Manzari's model will be named SANISAND henceforth. The automatic calibration procedure for SANISAND proposed in this article was applied to the experimental results of monotonic triaxial tests performed on crushed glass.

2 METHODOLOGY

This automatic calibration procedure is straightforward when addressed as a mathematical optimization problem subject to minimizing the objective or cost functions. This automation work minimizes the variance between these functions fetching different combinations of parameters within confined parameter space. NSGA-III assists in driving the system toward convergence (a state where further minimization of cost functions is impossible) with its efficient workflow. NSGA-III follows the biological evolution concept in which better solutions can be taken forward to further generations and delivers optimal solutions at the end of the prescribed generations. A predefined number of random initial parameter sets are chosen within given ranges and they generate the desired cost functions. The proceeding from the current first generation to the next generations involves crossovers, mutations, ranking of parameter sets, etc. Further details can be found in Deb et al. (2002) and Vallurupalli (2020). Henceforth the defined objective functions are minimized after optimizing for several generations thus generating a Pareto front (a front with optimal solutions). The parameter set corresponding to the solution with less variance with respect to formulated cost functions is considered a calibrated set. This calibration method associated with NSGA-III and SANISAND element tests to minimize the approximation error is well coordinated and monitored with python scripting. The same automation can be done with single objective optimization techniques where all the objective functions have to be integrated as a single function with appropriate weight factors. This study demands manifold element test simulations. The Dafalias and Manzari (2004) model was implemented in a UMAT-Fortran standard (Prada Sarmiento, 2011) and was compiled with Incremental Driver (Niemunis, 2008), a standalone program to integrate any constitutive law in a single Gauss point to simulate element tests under any stress, strain or mixed controlled conditions.

The objective functions have been developed in such a way that they define the error between the tests & SANISAND simulations corresponding to deviatoric stresses (q), mean effective stresses (p'), and volumetric strains (ε_v) individually at a given strain increment. This error has been estimated using conventional R-square error adapting no weighting factors. As each comparison comprises of three R-square estimations, these multiple accuracies have not been shown in the results. Crushed glass material was chosen to test the robustness of this calibration strategy using non-conventional materials, where the standard manual procedure to calibrate constitutive models cannot deliver adequate results. In this research, monotonic consolidated drained triaxial (CD) and undrained triaxial (CU) tests were performed on crushed glass under different confining pressures with varying relative densities which are discussed in detail in later sections.

3 VERIFICATION OF THE METHOD

The established automatic calibration system must be verified for its forecast quality. Therefore, the method was examined in this research by comparing its findings with previously published manual calibration results from Ramirez et al., (2018) and Yang et al., (2019).

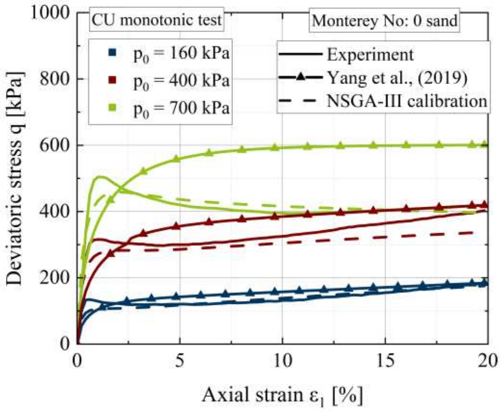

Figure 1. Comparison between the SANISAND simulations from Yang et al., (2019) and NSGA-III calibration.

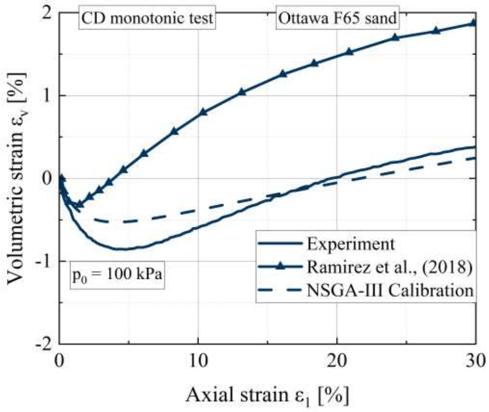

Figure 2. Comparison between the SANISAND simulations from Ramirez et al., (2018) and NSGA-III calibration.

Better-fitting SANISAND parameters have been produced when calibrated with optimization techniques, as seen in Figure 1. Besides, this approach significantly improved softening and peak shear strength in q-ε_1 curves especially in an undrained test prediction using

Monterey No: 0 sand. As far as the drained triaxial test with Ottawa sand F65 with 40% relative density is concerned, the automation approach delivered a far better fit between the test and simulation results (Figure 2). Other simulation results from these works with different drainage conditions and relative densities have also been compared and more accurate approximations with automated calibration were encountered, thereby verifying the proposed method.

4 EXPERIMENTS ON CRUSHED GLASS

The monotonic triaxial tests were carried out on strain-controlled conditions as adopted in Wichtmann (2005). The monotonic triaxial tests were performed on samples having a height and diameter of 20 and 10 cm respectively. The samples were prepared by air pluviation. The adopted displacement rate was 0.1 mm/min. Axial deformation of the specimen was measured with a displacement transducer mounted to the load piston at the top of the triaxial device. The volume change of the specimen was measured through a burette system using a differential transducer. Further details about the device and test procedures may be found in Sarkar et al. (2019). Table 1 presents the set of tests performed. The letters L, M, and D refer to the samples with low (45%), medium (55-65%), and dense (75%) initial relative densities. These tests were also performed with a second triaxial device which yielded similar results and hence can be assumed that they are reproducible. In this study, some tests were used for calibration (denoted as 'CAL'), and the rest for validation (denoted as 'VAL') to enable the independent validation of the results with the resulting parameter set.

Table 1. Experiment data considered for the calibration (CAL) and validation (VAL) with different relative density conditions (L-Loose, M- Medium, D-Dense).

Confining pressure (kPa)		**CU tests**		**CD tests**
50	-	-	-	CAL
80	CAL	-	CAL	VAL
100	VAL	CAL	VAL	-
150	-	VAL	-	-
200	-	-	-	CAL
300	CAL	CAL	CAL	-
Relative density	**L**	**M**	**D**	**L**

5 CALIBRATION OF SANISAND PARAMETERS

Dafalias and Manzari (2004) model has 15 constitutive parameters. Two fabric dilatancy parameters (z_{max} and c_z) control the model response under cyclic loading (Ramirez et al., 2018). Hence, they were not considered in the present calibration, where only monotonic triaxial tests were used. A sensitivity analysis was performed on the 13 remaining parameters for both monotonic CD and CU triaxial tests. Based on an extensive literature review (Sarkar, 2023), feasible ranges for each parameter were defined and confined to a specific parameter space for this optimization. Though in Table 2, 13 parameters are listed (excluding fabric dilatancy parameters), only 12 parameters are considered replacing M_c and c with critical friction angle to reduce the problem's dimensionality. With a calibrated critical friction angle, M_c and c can be calculated.

Table 2. Calibrated SANISAND parameters

SANISAND parameters	**Values**
Elasticity:	
Elastic material constant ($\boldsymbol{G_0}$)	100
Poisson's ratio ($\boldsymbol{\nu}$)	0.05
Critical state:	
CSL slope – compression ($\boldsymbol{M_c}$)	1.648
Ratio of CSL slope in extension and compression ($\boldsymbol{c}$)	0.645
Steady-state line constant ($\boldsymbol{\lambda_c}$)	0.052
Void ratio at p=0 ($\boldsymbol{e_0}$)	0.929
Steady-state line constant ($\boldsymbol{\xi}$)	0.912
Yield surface constant ($\boldsymbol{m}$)	0.049
Plastic modulus:	
Material constant 1 ($\boldsymbol{h_0}$)	2.30
Material constant 2 ($\boldsymbol{c_h}$)	0.83
Stress image constant on boundary surface ($\boldsymbol{n^b}$)	0.70
Dilatancy:	
Dilantancy material constant ($\boldsymbol{A_0}$)	0.73
Stress image constant on dilatancy surface ($\boldsymbol{n^d}$)	3.024
Fabric-dilatancy tensor*:	
Maximum fabric tensor factor (z_{max})	4
Controlling parameter of the pace evolution of z ($\boldsymbol{c_z}$)	600

**Not considered in the calibration*

The automatic calibration has been performed with NSGA-III in which the number of outer and inner divisions assist in generating the initial number of random parameter sets for the first generation. The number of generations can be tricky to choose and may need more generations depending on the complexity of the problem. This crushed glass calibration has achieved convergence with 7 outer divisions optimized for 100 generations. Default values for crossover, mutation, and distribution index that have been listed in Vallurupalli (2020), were used in this work.

For each CU test, two objective functions (R-square error functions) defining q and p$'$ error estimates, and for the CD test, functions with respect to q and ε_v error estimates can be formulated. Initially, this calibration was performed considering only barotropic and pycnotropic effects individually. Thereafter, all the conditions stated in Table 1 were calibrated together with this tool.

The mean stresses, deviatoric stresses, and volumetric strains were considered up to 15% of the axial strain in this calibration course. The q-p' and q-ε_1 curves using the final calibrated parameter set are shown in Figures 3 and 4.

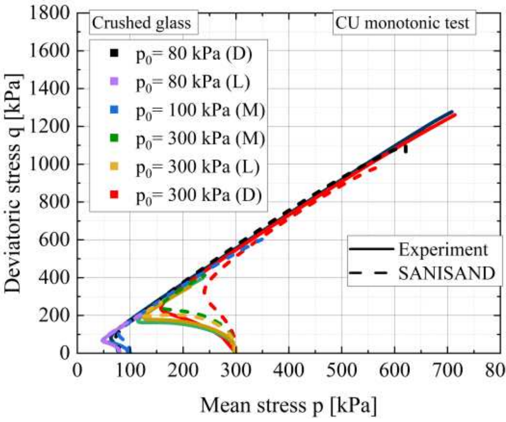

Figure 3. Comparison of SANISAND calibrated results with undrained triaxial experiments in q-p' space. (L, M, and D represent loose, medium, and dense materials respectively).

The CU triaxial simulation q-p' stress paths shown in Figure 3 exhibit good agreement between the tests and SANISAND. The initial stiffness obtained for $p_0 = 300$ kPa is slightly compromised in its accuracy as the parameter G_0 remains the same (independent of density in this model) which has to satisfy different relative density tests. An attempt has been made to minimise this variation by altering Poisson's ratio alone, but it affects the q-ε_1 behaviour drastically.

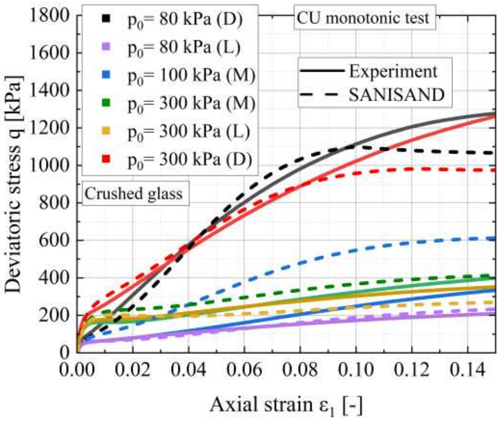

Figure 4. Comparison of SANISAND calibrated results with undrained triaxial experiments in q-$\mathcal{E}_1$ space. (L, M, and D represent loose, medium, and dense materials respectively).

However, the other tests were accurately simulated with the same set of parameters. The CU triaxial q-ε_1 plots in Figure 4 produced satisfactory results except for the simulation corresponding to medium-dense crushed glass with $p_0 = 100$ kPa. The simulation overpredicted the deviatoric stresses for larger axial strains in this case. This discrepancy in simulations can be improved by considering additional tests with different relative densities for $p_0 = 100$ kPa. Besides, this can be at times possible when the single selected parameter set must justify numerous tests with different conditions.

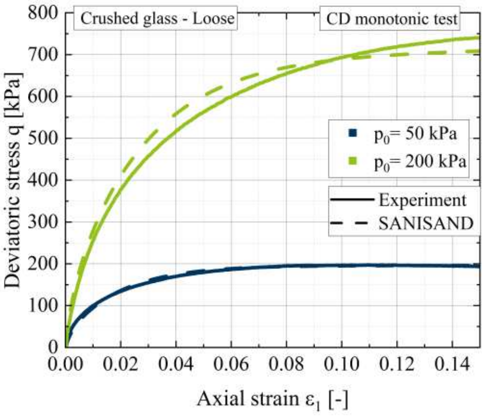

Figure 5. Comparison of SANISAND calibrated results with drained triaxial experiments on loose material in q-$\mathcal{E}_1$ space.

Despite that, SANISAND produced similar results for all the remaining test conditions. From Table 1, it can be seen that limited triaxial CD tests were conducted and included in this analysis. Calibrated CD test results for initial confining pressures of 50 kPa and 200 kPa are presented in Figures 5 and 6. In this optimization, the agreement between experimental and simulated q-ε_1 curves is accurate, describing hardening.

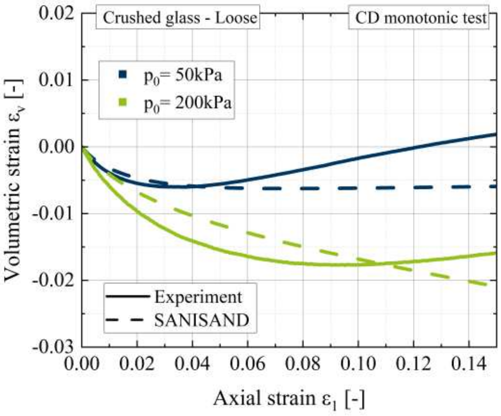

Figure 6. Comparison of SANISAND calibrated results with drained triaxial experiments on loose material in $\mathcal{E}_v$-$\mathcal{E}_1$ space.

The simulated results of contraction behaviour with this optimized parameter set are acceptable in predicting the material response under drained conditions. Since the volumetric strain has certain discrepancies (Figure 6), the dilation and contraction behavior have been analyzed with a single drained test optimization, and more accurate results were observed. However, the accuracy has been slightly compromised (within an acceptable range) when a unique parameter set has to satisfy different test results. Based on the numerical simulations, one weakness of the model is, that it cannot reach an asymptotic behaviour in the volumetric strain for certain conditions (eg. with high confining pressures). Besides, the constitutive parameter c, which is the ratio of the slopes of the critical state line in extension and compression, influences this dilatancy. In some literature (Ramirez et al., 2018; Wichtmann et al., 2019), this *c* has been roughly estimated to fit the test results rather than calculating from the critical friction angle. However, this has not been investigated in this study and this might influence the volumetric strain response. Regardless, this calibration yielded an optimal parameter set that depicts similar model responses for most cases.

6 VALIDATION OF THE PARAMETER SET

Specific tests not included in the calibration were used to ensure the robustness of the derived calibrated parameters (denoted as 'VAL' in Table 1). Afterwards, the resulting simulations were compared with the experiments to examine the approximations. Notably, the tests considered for validation had to be within range of the calibrated experiments (see Table 1).

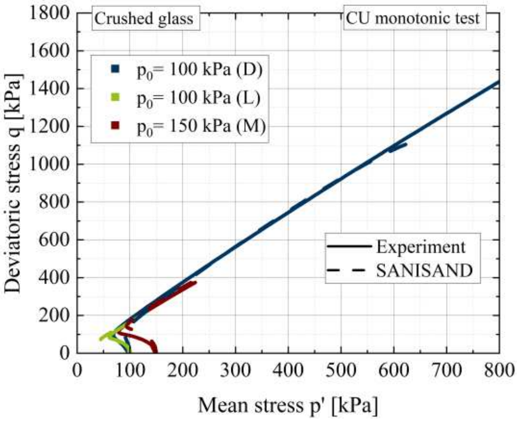

Figure 7. Comparison of SANISAND validated results with undrained triaxial experiments in q-p' space. (L, M, and D represent loose, medium, and dense materials respectively).

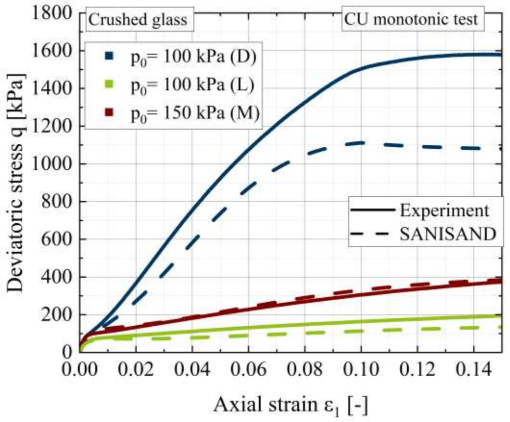

Figure 8. Comparison of SANISAND validated results with undrained triaxial experiments in q-ε_1. (L, M, and D represent loose, medium, and dense materials respectively).

For triaxial CU tests, despite minor differences in the initial stiffness in q-p' plots (Figure 7), the calibrated parameter set simulated stress behavior accurately. Though these parameters simulated better responses for other tests in q-ε_1 plots, they underestimated the shear strength of the dense material of about 300 kPa for the test with p_0 = 100kPa (Figure 8). As discussed in the previous sections, these uncertainties for one or two tests can be possible as the parameters should deliver satisfying fits for a wide range of test conditions. Hence, individual test accuracy in a few cases can be affected.

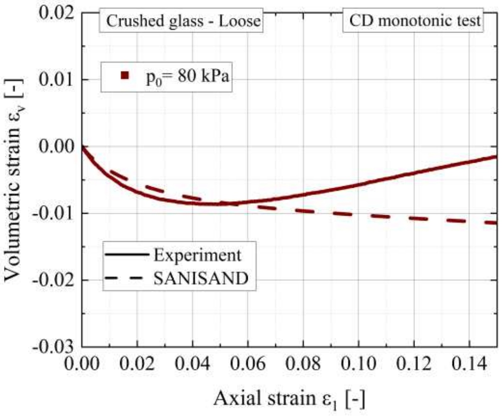

Figure 9. Comparison of SANISAND validated results with drained triaxial experiments on loose material in ε_v-ε_1.

The validation for the triaxial CD tests has been performed only on a single test with p_0 = 80kPa as only three drained tests were considered for this research. It can be seen from Figure 9, that the accuracy of describing the contraction is questionable. This calibration procedure was repeated by incorporating weighting factors that assign relative importance to the test objectives as their magnitudes are of different scales.

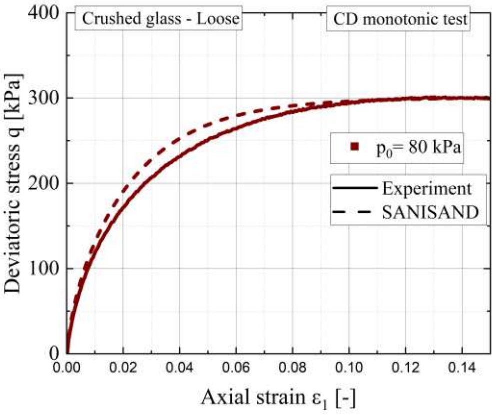

Figure 10. Comparison of SANISAND validated results with drained triaxial experiments on loose material in q-ε_1.

Yet again, the dilatancy misfit was observed. This could be because only two drained tests were considered for calibration. Besides, in many published literature, the parameter c is not clearly defined and has been considered randomly but not specified as the ratio of slopes of the critical state line in extension to compression. Nonetheless, the corresponding q-ε_1 behaviour from SANISAND (Figure 10) is accurate. Even so, these results with this calibrated parameter set have shown a better model response than existing hand calibration results satisfying different triaxial test conditions. Further investigation has to be done to analyse this effect and make this procedure more reliable.

7 CONCLUSION

An automated calibration procedure was developed for constitutive models by incorporating multi-objective optimization techniques. NSGA-III algorithm was applied to calibrate SANISAND parameters on crushed glass material. For this purpose, several experiments that were conducted under different barotropic and pycnotropic conditions were included in the calibration. A parameter set was derived from calibrating these tests, resulting in less discrepancy between the experiment and simulations. This set was verified for its robustness by validating with other test results. Though the results of a few tests underestimate the deviatoric stresses and volumetric strains, the findings are far better and therefore recommended than using hand calibration.

Incorporating techniques like validation strategy by checking parameters in the course of this optimization assists in avoiding certain easy mistakes that can persist in automatic calibration. This facilitates the application of the SANISAND model in advanced numerical problems with the current calibrated parameters. For future work, additional drained tests must be conducted on the crushed glass with different relative densities to consider in this calibration. A study has to be undertaken on parameter *c* with different values to see its influence on dilatancy and contraction. This analysis may enhance the findings corresponding to the contraction in drained triaxial tests.

8 ACKNOWLEDGMENTS

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