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Extended experimental database of Fontainebleau sand (NE34) and validation of hypoplastic constitutive models

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ABSTRACT: The design and analysis of (offshore) geotechnical structures require advanced and accurate finite element simulations, which involve constitutive models for the reproduction of mechanical soil behavior. To accurately describe the soil response under various loading conditions, these constitutive models must be calibrated and validated against extensive experimental data. Fontainebleau sand (NE34) is frequently utilized in model, centrifuge, and laboratory tests within offshore geotechnics, as detailed by Lascarro et al. (2024). Numerous numerical simulations are performed and constitutive models are calibrated from this experimental database. This study presents new laboratory tests on fresh NE34 sand to expand the existing database. The novel experimental results encompass a wide range of test conditions, including monotonic, cyclic, and for the first time drained high-cyclic tests (number of cycles $N = 10^5$). This comprehensive array of test conditions allows for an in-depth study of the deformation, strain accumulation, and excess pore water pressure accumulation behavior of NE34 sand. The new test data are compared to existing experimental results performed on older batches of NE34 sand and reveal potential variations in the mechanical properties of NE34 across different batches. Moreover, previously published parameter sets for the advanced constitutive models, namely hypoplasticity with intergranular strain (HP + IS) and hypoplasticity with intergranular strain anisotropy (HP + ISA), are tested using the new experimental results. The high-cycle accumulation model (HCA) for sand is additionally calibrated using the new drained high-cyclic tests. This analysis enables the verification of consistency between the existing and newly conducted test results, as well as the validation of the HP + IS and HP + ISA parameter sets.

Keywords: Experiments; Fontainebleau NE34 sand; Hypoplasticity; Intergranular Strain, High-Cycle Accumulation Model

1 INTRODUCTION

The design of geotechnical structures such as foundations, tunnels, or embankments requires nowadays advanced numerical simulations considering the overall complex mechanical behavior of soil. In offshore geotechnics, structures are subjected to complex loading conditions, including high-cyclic and multi-dimensional loads. Advanced constitutive models are essential for accurately capturing soil behavior under these conditions and for providing reliable predictions. However, these models and their parameters need to be calibrated using experimental data, obtained from an extensive range of laboratory tests. Besides the calibration procedure, it is equally important to validate the calibrated parameters using additional element and model tests. This validation ensures the reliability of both the constitutive models and the calibrated parameters for the specific soil being analyzed, as well as for subsequent numerical simulations.

Fontainebleau sand (NE34) is an extensively studied and widely used coarse-grained soil in the literature, including numerous laboratory, centrifuge and model tests (e.g. Yang et al., 2010; Altuhafi and Jardin, 2011; Sim et al., 2013; Taiba et al., 2018). As a result, an extensive experimental database is available. Dano et al. (2024) provide a compilation of the physical and mechanical properties of NE34 sand. This makes NE34 sand a frequently used material for calibrating, validating, and further developing constitutive models. For example, the advanced constitutive models Hypoplasticity with Intergranular Strain (HP + IS) and Hypoplasticity with Intergranular Strain Anisotropy (HP + ISA) have already been calibrated for NE34 sand by Lascarro et al. (2024). In this paper, the results of index and laboratory tests are presented to characterize a new batch of NE34 sand and to expand the experimental database. The experimental program was further complemented with high-cyclic drained triaxial tests (Number of cycles $N = 10^5$) to investigate the accumulative behavior of NE34 sand for the first time. A parameter set for the High-Cycle Accumulation (HCA) model is calibrated, allowing the prediction of the long-term deformation behavior of NE34 sand subjected to high-cyclic

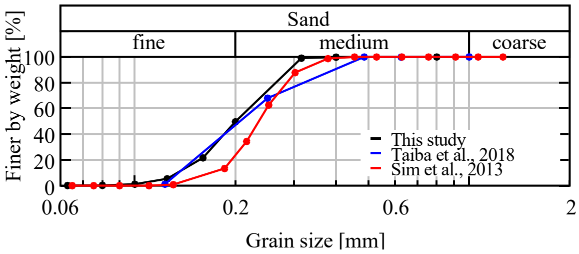

Figure 1. Grain size distribution of NE34 sand.

loading. These data are also used to validate the parameter sets for the HP + IS and HP + ISA models already available in the literature. Based on this characterization, the experimental results, and the validation of existing model parameters, potential variations in the mechanical properties of different batches of NE34 sand can be assessed.

2 TEST MATERIAL

The material used in this study is Fontainebleau NE34 sand, a sub-angular silica sand (Altuhafi and Jardin, 2011). It was sourced from the Nemours quarry, located south of Paris, and purchased by the company Sibelco. The sand was delivered in May 2023. Figure 1 shows the determined grain size distribution curve, along with two distributions reported in the literature (Sim et al., 2013; Taiba et al., 2018). The comparison reveals small differences between the distributions from the literature and those obtained in this study. In particular, the sand analyzed by Sim et al. (2013) exhibits larger grain sizes. Additionally, the minimum e_{min}, maximum e_{max} void ratio, grain density ρ_s, and critical friction angle φ_c were determined. The critical friction angle was measured using angle of repose tests. The index properties are summarized in Table 1, along with previously reported results from the literature. Minor deviations are observed between the values reported in the literature and those obtained in this study. It should be noted that the index tests in this study followed German standards DIN, while other standards may have been used in the literature. For example, Taiba et al. (2018) employed the ASTM D4253 standard to determine the maximum e_{max} and minimum e_{min} void ratio.

3 EXPERIMENTAL PROGRAM

A variety of laboratory tests were conducted to expand the existing experimental database for NE34 sand. These included four oedometric tests (OE_), four monotonic drained triaxial tests (TMD_), one monotonic drained triaxial test with un- and reloading cycles (TMCD1), three cyclic undrained triaxial tests (TCU_) up to liquefaction and five high-cyclic drained

Table 1. Index properties of NE34 sand.

Index Properties	This study	Taiba et al. (2018)	Sim et al. (2013)	Lascarro et al. (2024)
ρ_s [g/cm^3]	2.659	2.642	2.65	2.65
e_{max} [−]	0.887	0.950	0.90	0.882
e_{min} [−]	0.547	0.645	0.51	0.510
D_{50} [mm]	0.201	0.216*	0.235	0.21
C_u [−]	1.659	1.677*	1.453*	1.53
φ_c [°]	31.4	-	-	-

* Calculated based on the grain size distributions shown in Figure 1.

Table 2. Oedometric, monotonic and cyclic undrained tests on NE34 sand.

Test	e_0 [−]	D_{r0} [−]	p_0 [kPa]	q_0 [kPa]	q^{ampl} [kPa]
OE1	0.573	0.92	-	-	-
OE2	0.550	0.99	-	-	-
OE3	0.782	0.31	-	-	-
OE4	0.768	0.35	-	-	-
TMD1	0.576	0.91	50	0	-
TMD2	0.570	0.93	100	0	-
TMD3	0.837	0.15	100	0	-
TMD4	0.555	0.98	300	0	-
TMCD1	0.557	0.97	100	0	-
TCU1	0.656	0.68	100	0	20
TCU2	0.684	0.60	100	0	25
TCU3	0.674	0.63	100	0	30

Table 3. High-cyclic drained triaxial tests on NE34 sand.

Test	e_0 [−]	D_{r0} [−]	p^{avg} [kPa]	q^{avg} [kPa]	q^{ampl} [kPa]
TCD1	0.557	0.97	200	150	60
TCD2	0.796	0.27	200	150	60
TCD3	0.793	0.28	200	150	60
TCD4	0.667	0.65	200	150	60
TCD5	0.670	0.64	200	150	80

triaxial tests (TCD_, Number of cycles $N = 10^5$). Tables 2 and 3 provide an overview of the conducted tests, including the initial void ratio e_0, initial relative density $D_{r0} = (e_{\text{max}} - e_0)/(e_{\text{max}} - e_{\text{min}})$, initial mean effective pressure p_0 and initial deviatoric stress q_0. For the cyclic tests, the applied deviatoric stress amplitude q^{ampl} is also presented. In the case of the high-cyclic drained tests, the average values of mean effective pressure p^{avg} and the deviatoric stress q^{avg} during the test are included. All tests presented in this study were prepared using the air pluviation technique.

Two oedometric tests were performed using samples that were initially loose and two oedometric tests were conducted on initially dense samples. The results are presented in Figure 2. Throughout the tests, multiple un- and reloading cycles were applied. The dense samples exhibit higher stiffness compared to the loose samples. Furthermore, all four tests show

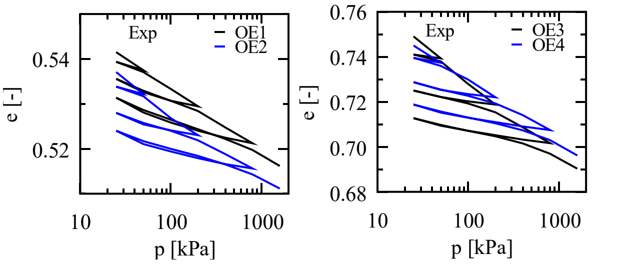

Figure 2. Oedometric test results on dense (left) and loose (right) NE34 sand.

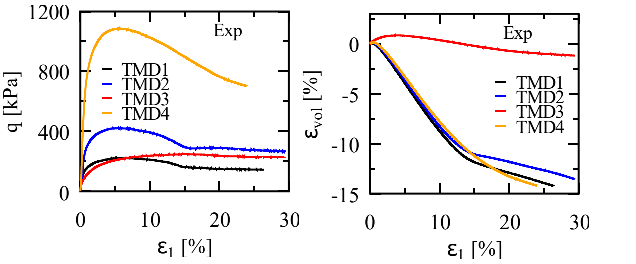

Figure 3. Drained monotonic triaxial test results on NE34 sand with different initial mean effective pressures and densities.

increased stiffness during un- and reloading up to the virgin loading line.

The results of the drained monotonic triaxial tests are shown in Figure 3. Three dense samples (TMD1, TMD2 and TMD4) were tested under different lateral stresses σ_3. All three samples exhibit a peak in deviatoric stress q before decreasing to a residual value. The course of the volumetric strain $\varepsilon_{\mathrm{vol}}$ is similar for all three samples. An additional sample (TMD3) was tested in a loose state. This sample does not reach a peak strength; instead the deviatoric stress q increases monotonically during the test until it reaches a residual value. This residual value is equivalent to that of the dense sample under the same lateral stress σ_3. In comparison to the dense samples, the loose sample exhibits greater contractancy, followed by slight dilatancy. The average residual shear strength from the four tests is $\varphi_c = 33.5\,°$ which is higher than the critical friction angle φ_c determined from the angle of repose test. The critical state is not reached in some of the tests, as evidenced by continued volumetric deformation. In the literature, critical friction angles φ_c of $32.6\,°$ (Sim et al., 2013) and $33\,°$ (Altuhafi and Jardine, 2011) have been reported for triaxial compression tests, while a value of $32.8\,°$ was determined from a direct shear test (Yang et al. 2010). The slight variations in these values may be attributed to minor differences in the grain size distribution curves. Figure 4 shows the results of a monotonic drained triaxial test with unloading and reloading at axial strains ε_1 of $4, 8, 12, 16, \text{and } 20\,\%$. For comparison, the two monotonic drained tests conducted at the same lateral stress, $\sigma_3 = 100\,\text{kPa}$, are also included. During the unloading and reloading

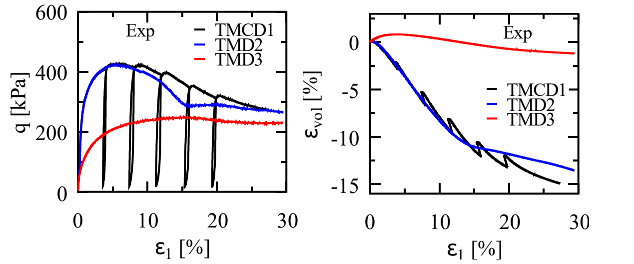

Figure 4. Drained monotonic triaxial tests with multiple un- and reloading stages on NE34 sand.

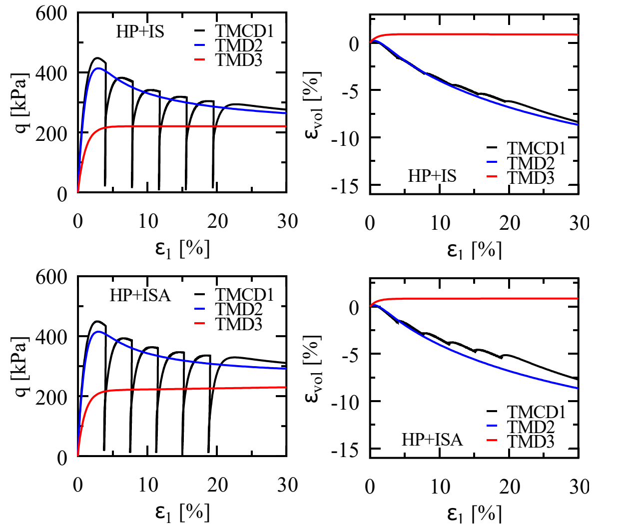

Figure 5. Simulations of drained monotonic triaxial tests with multiple un- and reloading stages using HP + IS (top) and HP + ISA (bottom).

cycles, significantly higher stiffness is observed compared to the reference monotonic test TMD2, which has a similar initial relative density as TMCD1. Apart from this, the test curves are very similar, displaying comparable peak and residual shear strengths.

The results of the three cyclic undrained tests are shown in Figure 6. These tests provide valuable insights into soil behavior and the development of pore water pressure under undrained conditions, which are commonly assumed during seismic events. Furthermore, they are essential for calibrating constitutive models that capture cyclic loading effects. All tests started at the same initial isotropic mean effective stress, $p_0 = 100\,\text{kPa}$, and a similar initial medium-dense to dense state. The deviatoric stress amplitude q^{ampl} was varied between the tests. In each test, a decrease of the effective mean pressure is observed, resulting in a build-up of excess pore water pressure, leading to the liquefaction ($p = 0\,\text{kPa}, q = 0\,\text{kPa}$) of the sample. After liquefaction, all samples exhibit the well- known butterfly-shaped stress paths, along with increasing axial strain ε_1. The number of cycles required to reach initial liquefaction decreases as q^{ampl} increases.

Five high-cyclic drained triaxial tests ($N = 10^5$)

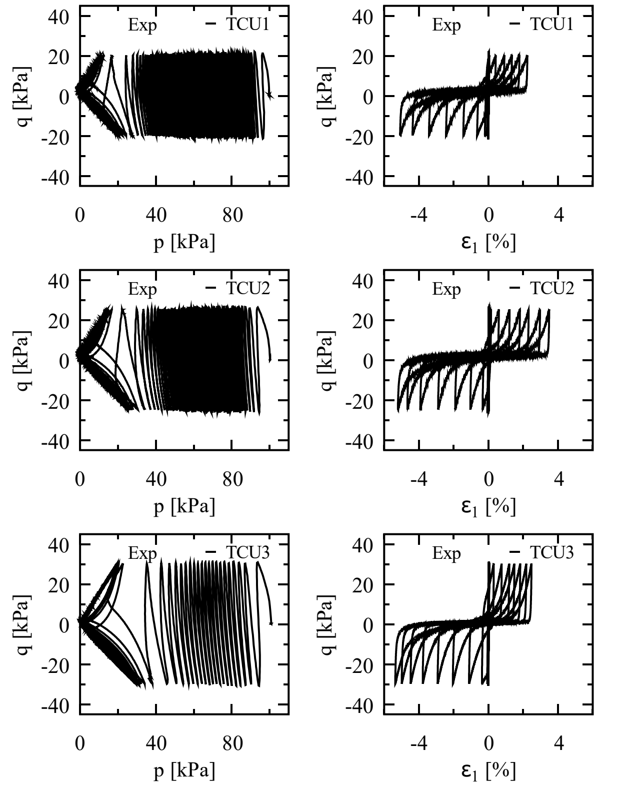

Figure 6. Undrained cyclic triaxial tests on NE34 sand.

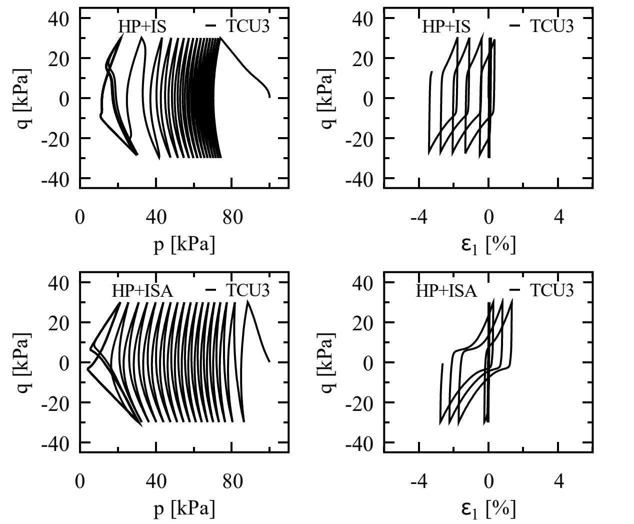

Figure 7. Simulations of TCU3 using HP + IS (top) and HP + ISA (bottom).

were conducted on NE34 sand. These tests facilitate the investigation of long-term deformation behavior under small load cycles, essential for assessing the deformation of monopiles subjected to wind and wave loading and for calibrating constitutive models for high-cyclic loading. During these tests, stress cycles with a deviatoric stress amplitude of $q^{\text{ampl}} = 60\,\text{kPa}$ were applied to the samples at a frequency of $0.2\,\text{Hz}$, while measuring the axial strain ε_1 and the volumetric strain ε_{vol}. TCD5 was conducted with a higher deviatoric stress amplitude of $q^{\text{ampl}} = 80\,\text{kPa}$. Also the initial relative densities of the samples varied

Table 4. Validated HP Parameter (Lascarro et al. 2024).

φ_c	h_s	n	e_{i0}	e_{c0}	e_{d0}	α	β
31.6°	4800 MPa	0.29	0.99	0.882	0.51	0.15	1.96

Table 5. Validated IS Parameter (Lascarro et al., 2024).

R	m_R	m_T	χ	β_R
10^{-4}	5	2	6.3	0.45

Table 6. Validated ISA Parameter (Lascarro et al., 2024).

R	m_R	β_{h0}	β_{hmax}	χ_0	χ_{max}	c_a	c_z
10^{-4}	5	0.25	3	5	12	0.1	300

across the tests. It is important to note that the initial void ratios e_0 listed in Table 3 correspond to the void ratio after the irregular first cycle. This first cycle is termed irregular because the deformations observed during it can differ significantly from those of the subsequent loading cycles. For the analysis of drained high-cyclic tests and calculations with the HCA model, this irregular cycle is typically excluded (Wichtmann, 2016). Figure 8 shows the accumulated strain $\varepsilon^{\text{acc}} = \sqrt{(\varepsilon_1^{\text{acc}})^2 + 2(\varepsilon_3^{\text{acc}})^2}$ over the number of cycles N for each test. It can be seen that the loose samples undergo greater deformation compared to the denser samples. Test TCD3 was a replication of test TCD2, and the two tests show a similar progression of accumulated strains ε^{acc} over the test duration. This confirms the reproducibility of the test results.

4 VALIDATION OF TWO HYPOPLASTIC CONSTITUTIVE MODELS

Hypoplastic constitutive models offer an advanced framework for describing the highly non-linear, path-dependent mechanical behavior of granular soils under varying stress and density conditions. These models do not distinguish between an elastic and a plastic strain rate, like in elasto-plastic formulations.

The Hypoplasticity after von Wolffersdorff (1996) (HP) has proven to be suitable for the simulation of monotonic deformation of granular materials. However, it underestimates the stiffness during stress or strain reversals, which leads to an overestimation of cyclic deformations during unload and reload scenarios (so-called ratcheting). To overcome this shortcoming, the Intergranular Strain (IS) concept, which memorizes the most recent deformation history, was introduced by Niemunis and Herle (1997). In the coupled HP+IS model, the stiffness is increased and the plastic deformation is decreased upon a reversal of loading. The HP+IS is nowadays widely used for the simulation of complex loading scenarios for granular soil.

Numerous modified IS concepts have been introduced to enhance the original approach, including

Table 7. Calibrated HCA Parameters.

C_{ampl}	C_e	C_e	C_Y	C_{N1}	C_{N2}	C_{N3}
1.7	0.4	0.46	2.26	$6.5*10^{-4}$	0.04	$3.8*10^{-5}$

the ISI method by Duque et al. (2020) and the GIS method by Mugele et al. (2024). The Intergranular Strain Anisotropy (ISA) concept (Fuentes and Triantafyllidis, 2015) differs fundamentally from other modifications, as it uses an elasto-plastic evolution of the intergranular strain. In the version of Fuentes et al. (2020), the coupled HP+ISA model includes also fabric and cyclic preloading effects.

Lascarro et al. (2024) calibrated parameter sets for HP+IS as well as HP+ISA for NE34 sand. The parameter sets are listed in Tables 4 to 6. Both are validated in this work using the new test data. The recalculations are performed using the element test program IncrementalDriver and user material (umat) Abaqus subroutines provided by D. Mašín for HP+IS and W. Fuentes for HP+ISA. Both subroutines can be downloaded from soilmodels.com. More details on the constitutive models, the procedure, and the initialized state variables can be found in Lascarro et al. (2024).

The simulations of the monotonic and cyclic tests are shown in Figure 5 and Figure 7. The performance of both constitutive models described in Lascarro et al. (2024) is confirmed. Both models provide a very similar response due to a monotonic deformation, which corresponds to the same base model of HP. Under cyclic deformation, HP+ISA provides a more realistic prediction of experimental observations by accounting for fabric change effects. However, neither model accurately simulates strain evolution during the cyclic mobility (post-liquefaction) stage, a limitation recently addressed by Tafili et al. (2024) for hypoplastic models.

5 CALIBRATION OF THE HIGH-CYCLE ACCUMULATION MODEL

The High-Cycle Accumulation (HCA) model (Niemunis et al., 2005; Wichtmann, 2016) describes the accumulative deformation behaviour of soil under cyclic loading with small strain amplitudes ($\varepsilon^{\mathrm{ampl}} \leq 10^{-3}$) and a large number of cycles ($N \geq 10^3$). It accounts for the accumulation of plastic strains over many load cycles, even if one individual cycle is too small to cause noticeable deformation. The HCA model thereby describes only the trend of the deformations without considering each cycle. The so-called explicit constitutive approach is numerically inexpensive and can be used to predict deformations of geotechnical structures subjected to high-cyclic loading, such as offshore foundations.

The HCA model has already been calibrated for

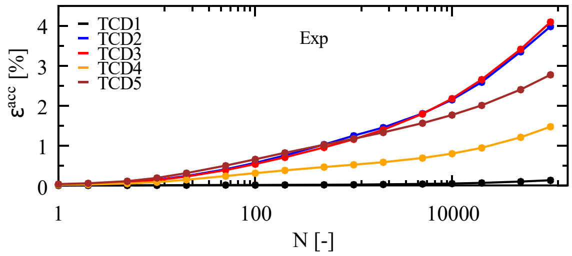

Figure 8. Drained high-cyclic triaxial tests on NE34 sand.

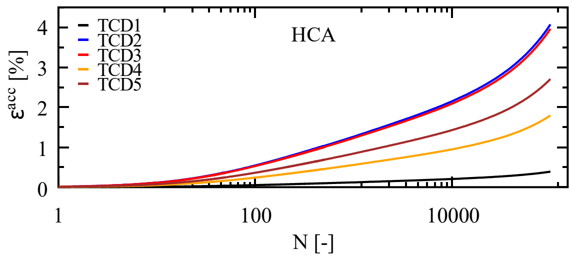

Figure 9. Back-calculation of drained high-cyclic triaxial tests with HCA Model.

many sands (Wichtmann, 2016), but not for the NE34 sand. Using the procedure proposed by Wichtmann et al. (2015), the HCA parameters can be estimated based on granulometric (d_{50}, C_{u}) or index properties (e_{min}) and further be modified using element test simulations. The calibrated HCA parameters for NE34 sand can be found in Table 7.

The recalculation of accumulated strain in the drained high-cyclic triaxial tests is shown in Figure 9. The HCA model thereby captures well the influence of the stress amplitude and the initial density on the nonlinear accumulation of strains. The calibrated HCA model for NE34 sand can further be used for the simulation of several thousand loading cycles in offshore applications.

6 CONCLUSION

Laboratory tests were conducted on Fontainebleau NE34 sand, accompanied by a characterization using index tests. These tests provide valuable complementary data to the existing experimental database for NE34 sand, and expand our knowledge of the material behavior under various conditions. A comparison of the characterization and laboratory test results with literature data confirmed that only minor differences exist between different batches of NE34 sand.

The experimental results were used to validate previously calibrated parameter sets for two hypoplastic constitutive models, HP+IS and HP+ISA. These parameter sets allow for the back-calculation of the new experimental data, thereby confirming their validity.

High-cyclic drained triaxial tests were performed for the first time to investigate the accumulative behavior of NE34 sand. These experimental data were then used to calibrate parameters for the HCA model. The calibrated parameter set of the HCA model now enables reliable predictions of the long-term deformation behavior of NE34 sand.

Further tests are planned to expand the database. These include time-independent partially drained triaxial tests (Zuern et al., 2024), as well as ring shear tests.

AUTHOR CONTRIBUTION STATEMENT

Zürn, J.: Data curation, Investigation, Writing- original draft. **Mugele, L.**: Formal analysis, Writing- original draft. **Stutz, H. H.**: Supervision, Writing- review & editing, Project administration, Funding aquisition. **Merita, T.**: Writing- review & editing **Wichtmann, T.**: Funding acquisition, Writing- review and editing

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