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Constitutive models for the cyclic soil-structure interaction of integral railway bridges

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ABSTRACT: Integral bridges with larger total spans exhibit intensified cyclic soil-structure interaction due to seasonal temperature fluctuations. To realistically model this behaviour under cyclic loading, appropriate soil constitutive models must be employed and calibrated under realistic conditions. This contribution investigates two elastoplastic (DeltaSand, Sanisand-MS) and two hypoplastic constitutive models (Hypo+IGS, Hypo+ISA) with regard to their performance under cyclic loading. The calibration of the material models is based on an extensive laboratory testing programme using a representative, highly compacted gravel backfill material. Subsequently, finite element simulations of the cyclic soil-structure interaction of an integral bridge are conducted to comparatively evaluate the constitutive models. All models show qualitatively similar patterns of cyclic earth pressure development across a wide range of bridge lengths. However, the settlement behaviour of the backfill differs in parts significantly. In particular, one hypoplastic model exhibits pronounced "overshooting" effects.

KEYWORDS: Cyclic loading, integral bridges, numerical analysis, hypoplasticity, DeltaSand, Sanisand-MS

1 INTRODUCTION

A research project supported by DB InfraGO AG at Graz University of Technology (Institute of Soil Mechanics, Foundation Engineering and Computational Geotechnics) addresses the cyclic soil-structure interaction (SSI) of longer integral railway bridges, cf. Stastny (2025). Laboratory tests, long-term measurements on actual structures, and 2D and 3D finite element (FE) parametric studies have been carried out. Several soil constitutive models have been calibrated and assessed with respect to their suitability to model the cyclic loading behaviour of integral bridges. The present contribution summarises the investigations published in Stastny et al. (2024) and Stastny et al. (2025a).

Integral bridges (Figure 1a) exhibit an enhanced cyclic interaction with their backfill. This is caused by horizontal deformations of the superstructure, especially due to recurring seasonal temperature changes (Figure 1b). As a consequence, laboratory experiments show cyclic increases of earth pressure behind the abutments (during summer conditions) and cyclic settlement accumulation at the backfill surface, cf. (England et al. 2000, Lehane 2011, Stastny 2025). To numerically reproduce the resulting cyclic interaction behaviour of the backfill as realistically as possible, suitable constitutive models for the mechanical behaviour of the soil are required. These must be calibrated for representative materials and in situ conditions.

This paper investigates two elastoplastic models (DeltaSand, Sanisand-MS) and two hypoplastic models (Hypo+IGS, Hypo+ISA) with a focus on their behaviour under cyclic loading. The constitutive models are first calibrated based on a comprehensive laboratory programme using a representative, highly compacted gravel backfill material (Figure 1c). For such well-graded, coarse-grained materials, no 1*g* or n*g* experiments on the cyclic SSI currently exist, and only a few calibrated parameter sets for constitutive models are available (Stastny et al. 2024). The simulation of the laboratory tests

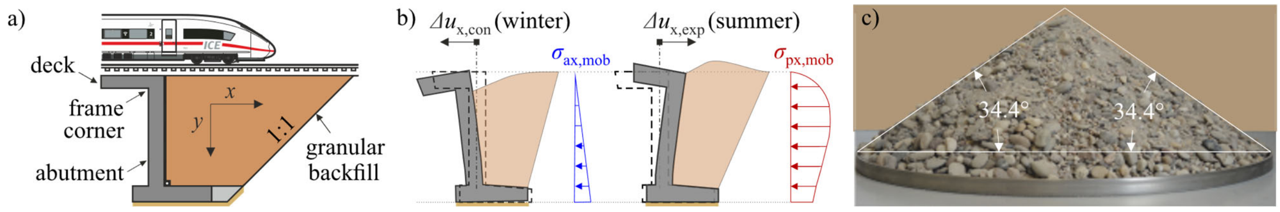

Figure 1.a) Illustration of an integral bridge abutment; b) cyclic soil-structure interaction of an integral abutment; c) investigated well-graded gravel backfill material, adapted from Stastny et al. (2024).

reveals, among other things, significant over- and undershooting effects in most of the investigated material models - i.e. overestimation or underestimation of shear strengths during reloading phases (Medicus et al., 2024; Tafili et al., 2024).

Subsequently, FE analyses are carried out to study the cyclic soil-structure interaction of integral bridges with different total lengths, aiming to compare the individual constitutive models. The focus lies on the cyclic evolution of earth pressure mobilisation behind the abutment and the settlement accumulation at the backfill surface. Additionally, supplementary studies are conducted to demonstrate the influence of abutment deformation on the mobilisation of lateral earth pressures.

2 MATERIAL AND EXPERIMENTAL TESTING

According to DB guideline Ril 836.4106 (2014), backfills of railway bridges in Germany must be constructed using well-graded sands or gravels with less than 5% fines (≤ 0.063 mm) and compacted in 30 cm layers to 100% Proctor density. The material must exhibit a coefficient of uniformity $C_U \geq 6$. The gravel backfill material examined in this study (GI, $d_{50} = 4$ mm, $C_U = 24$) complies with these requirements. The critical friction angle of the gravel is 34.4°, see Figure 1c. Further information on the material can be found in Stastny et al. (2024). A comprehensive experimental programme was carried out on the gravel, described in detail in Stastny et al. (2024) and Stutz et al. (2022). The programme is summarised in Table 1. The experiments include oedometer tests with repeated unloading and reloading cycles, as well as monotonic and cyclic triaxial tests under drained and undrained conditions. In addition, drained cyclic triaxial tests were conducted using bender elements (BE) and local strain measurements (LDT) analogous to Knittel (2020) and Knittel et al. (2020). All test series focus on highly compacted specimens in the range of modified Proctor density, in order to replicate in-situ conditions. The applied stress and loading conditions also correspond to the real conditions found in the backfills of integral bridges.

Table 1. Experimental programme from Stastny et a. (2024).

Test	**Specimen size & Preparation**	**D_{r0} [%]**	**p_0 [kPa]**
3x oedometric tests with un- and reloading	$h = 16$ cm, $d = 50$ cm, pluviation + vibration	6,8 91 93	-
3x drained monotonic triaxial tests strain-controlled	$h = 10$ cm, $d = 10$ cm, dry tamping	95 95 95	50 100 300
3x undrained cyclic triaxial tests stress-controlled	$h = 10$ cm, $d = 10$ cm, dry tamping	84 87 84	50 100 100
3x drained cyclic triaxial tests with BE and LDT stress-controlled	$h = 18{,}3$ cm, $A = 76$ cm², dry tamping	87 86 79	50 100 300

3 SOIL MODELS AND CALIBRATION

This contribution investigates the soil constitutive models listed in Table 2, which focus on cyclic loading: DeltaSand (Galavi, 2021), Sanisand-MS (Dafalias and Manzari, 2004; Liu et al., 2019), hypoplasticity according to von Wolffersdorff (1996) extended with intergranular strain (Hypo+IGS) based on Niemunis and Herle (1997), as well as the Intergranular Strain Anisotropy model (ISA) developed by Fuentes and Triantafyllidis (2015), Poblete et al. (2016), and Fuentes et al. (2020). Previous validations of these constitutive models have primarily focused on the material behaviour of (poorly-graded) sands, for which DeltaSand and Sanisand-MS were specifically developed. In the present work, the models are calibrated based on laboratory test results obtained for the backfill gravel. The goal of the calibration is to achieve the most consistent and realistic reproduction of all test results using a single parameter set for each model. Further details on the constitutive models, their calibration, and the resulting parameter sets are provided in Stastny et al. (2024, 2025a). Note: All stresses in this contribution are considered as effective stresses.

Table 2. Applied soil constitutive models.

Soil model	**Hypo+IGS**	**Hypo+ISA**	**Delta-Sand**	**Sanisand-MS**
Type	hypoplastic	hypoplastic	elastoplastic	elasto-plastic
Number of parameters	13	16	16	16

4 SIMULATION OF ELEMENT TESTS

Almost all laboratory tests listed in Table 1 were used for the calibration of the four constitutive models presented in Table 2 and subsequently reproduced numerically (based on the calibrated parameter sets). As an example, Figure 2 shows the numerical simulation of a very dense oedometer test ($D_{r0} = 93.1\%$) with 16 unloading and reloading cycles. The model responses display either slightly too stiff behaviour (Hypo+IGS) or slightly too soft behaviour (DeltaSand), but overall demonstrate an acceptable reproduction of the cyclic strain increments, particularly in light of the very stiff material behaviour with only minimal changes in void ratio. A numerical simulation of (nearly) all laboratory tests is provided in Stastny et al. (2024, 2025a). In general, the constitutive models are capable of adequately reproducing the laboratory test results. Stastny et al. (2024, 2025a) also present a detailed discussion of the strengths and limitations of the models.

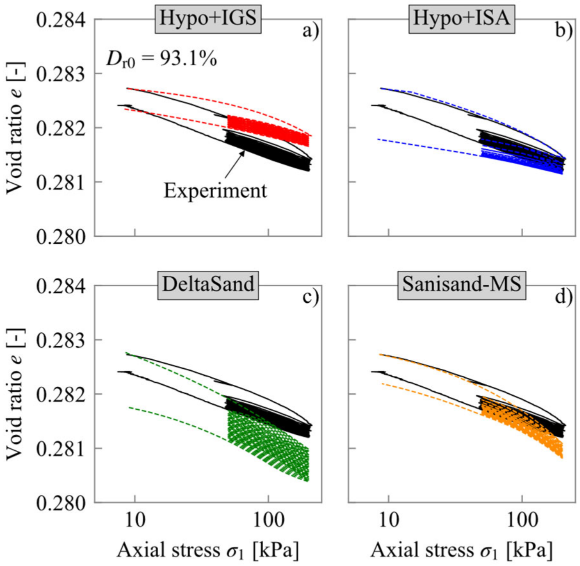

Figure 2. Numerical simulation of the oedometer test (black lines) with 16 unloading and reloading cycles using different constitutive models (dashed lines).

To validate the calibrated parameter sets, a drained triaxial test ($D_{r0} = 95.3\%$, $p_0 = 100$ kPa) with three unloading and reloading cycles was used, see Figure 3. The two hypoplastic models

(Hypo+IGS and Hypo+ISA) exhibit pronounced over- and undershooting effects, i.e. they tend to overestimate or underestimate the shear strength during reloading phases and do not always return to the “monotonic” loading path observed in the experiments. The behaviour can be attributed to an insufficient “memory” in the IGS formulation: In the case of Hypo+ISA, analyses by Medicus et al. (2024), Tafili et al. (2024) and Stastny et al. (2025a) indicate that the current formulation does not include a surface to limit stress paths as long as the current state lies within the ‘small strain’ yield surface of the ISA model. DeltaSand and Sanisand-MS reproduce the unloading and reloading behaviour in Figure 3 very well, showing no or only very minor over- or undershooting behaviour. Further analyses in Stastny et al. (2025a) reveal that, under repeated cyclic loading with constant strain amplitude, over- and undershooting effects become more pronounced in all material models - most notably in the two hypoplastic models, but also in Sanisand-MS and, to a lesser extent, in DeltaSand. Moreover, overshooting effects increase with rising relative density and were also observed in Stastny et al. (2025a) when using other calibrated parameter sets (e.g. for Karlsruhe fine sand). In drained boundary value problems subjected to constant cyclic loading amplitudes, overshooting effects may lead to a significant overestimation of stresses (see chapter 5) and/or an underestimation of soil deformations.

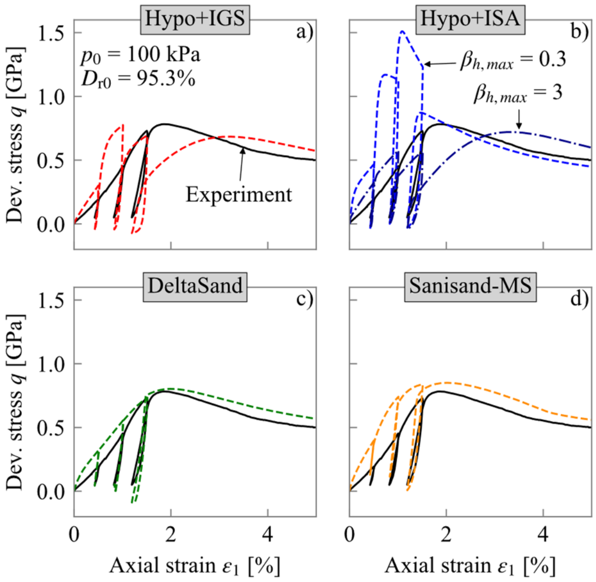

Figure 3. Numerical simulation of the drained triaxial test (black lines) with 3 unloading and reloading cycles using different constitutive models (dashed lines).

5 FINITE ELEMENT ANALYSES

The following chapter presents selected numerical studies on the cyclic soil-structure interaction (SSI) of an integral railway bridge. The objective is to compare the SSI behaviour using different constitutive models (Hypo+IGS, DeltaSand, Sanisand-MS) with previously calibrated parameter sets. Due to pronounced overshooting effects observed in element tests, the Hypo+ISA model was excluded. Various bridge lengths and abutment deformation patterns were analysed. The presented investigations originate from Stastny et al. (2024, 2025a).

5.1 *Modelling*

A simplified FE model of an integral bridge with total lengths of 40, 160, and 320 m and a constant abutment height of 8 m was used, see Figure 4. The model was created in Plaxis 2D with 15-noded finite elements (fourth-order shape functions), Version 23.2 (Bentley, 2023) (or in Plaxis 3D with second order 10-noded elements for Sanisand-MS), in drained conditions. The concrete abutment with spread footing was modelled using linear elastic volume elements. The deformation of the superstructure due to temperature was applied in a simplified manner as horizontal line displacements on the abutment side, to simulate different (foot) displacements. Interface elements were inserted between soil and abutment to allow relative displacements and represent the reduced shear strength in the contact zone. An interface strength reduction of $R_{\text{inter},\varphi} = tan(\varphi_{\text{inter}}) / tan(\varphi_{\text{soil}}) = 0.7 – 0.9$ was used.

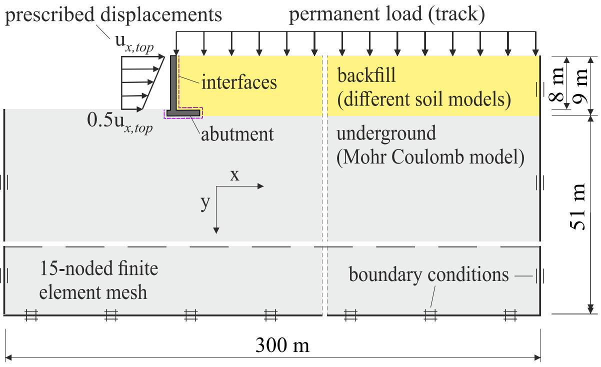

Figure 4. Schematic drawing of the 2D FE model with simplified line displacement of the abutment.

The backfill was assigned an initial relative density of D_{r0} = 80% and modelled using the different constitutive models (Hypo+IGS, DeltaSand, Sanisand-MS). The underground soil layer was simulated using a Mohr-Coulomb model to minimise its influence on the cyclic SSI behaviour of the backfill. In several calculation phases, the stepwise construction of the bridge was modelled, starting from an existing embankment. Subsequently, cyclic horizontal displacements of $u_{\text{x,top}}$ = ±5, 20, 40 mm (representative of bridges with total lengths of $L \approx 40$, 160, and 320 m) were applied to the abutment to replicate seasonal temperature-induced deformations of the superstructure over 20 summer-winter cycles. A simplified assumption of 50% translation at the abutment foot was adopted ($u_{\text{x,foot}}$ = ±2.5, 10, 20 mm). Further details on the modelling approach are provided in Stastny et al. (2025a). Note: The chosen modelling approach does not account for additional horizontal deformations due to creep and shrinkage, nor for seasonal temperature variations. Furthermore, the superimposed vertical dynamic loads from railway traffic were not considered. However, this is in line with the aim of the study, which primarily focuses on comparing material models for cyclic soil-structure interaction.

5.2 *Results*

Figure 5 (*middle column*) shows the horizontal stress distribution behind the abutment during winter (W) and summer (S) cycles 1, 2, 10, and 20, exemplarily for horizontal displacements of $u_{\text{x,top}}$ = ±40 mm. In the summer phases, all constitutive models exhibit a cyclic increase of earth pressure, while in the winter phases, the pressure decreases to the level of active earth pressure. DeltaSand and Sanisand-MS show a similar shape of earth pressure distribution with increasing number of summer cycles. In contrast, the Hypo+IGS model exhibits pronounced

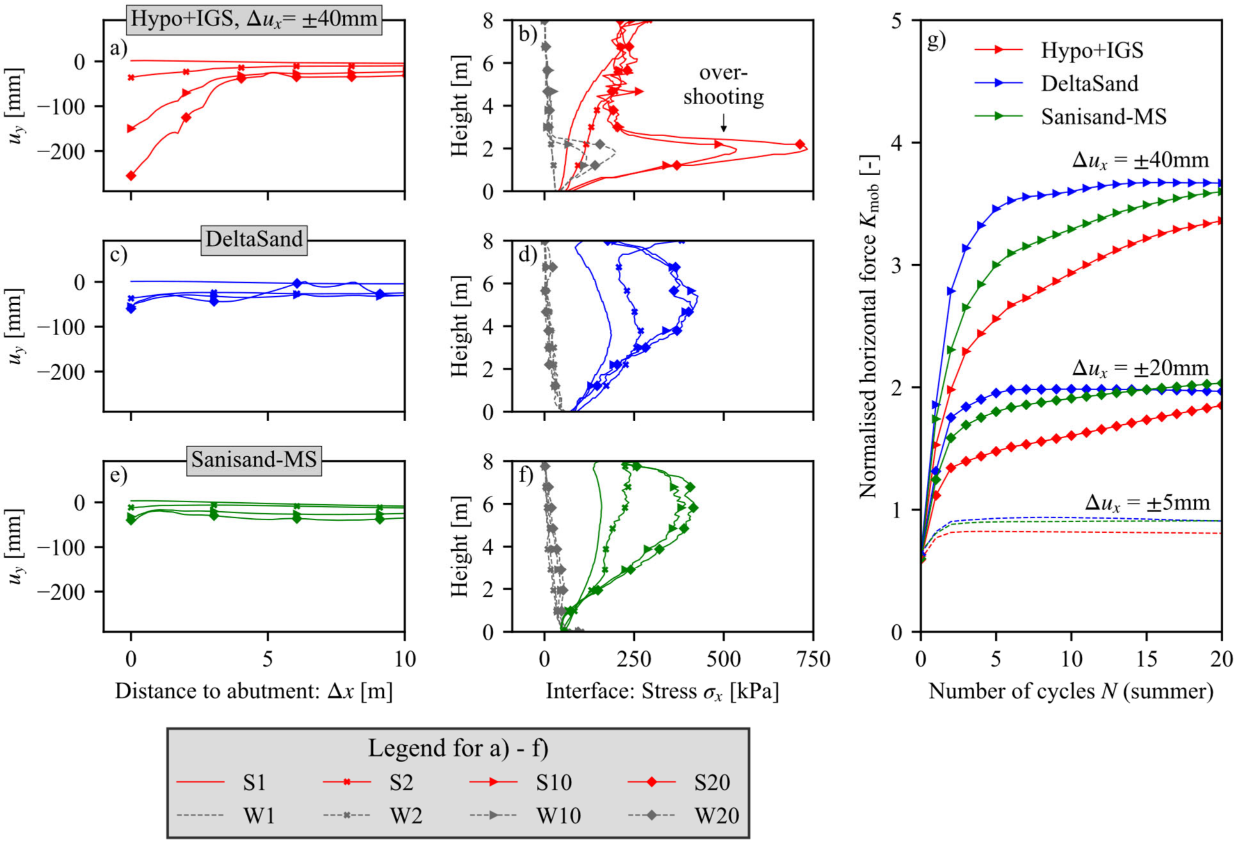

Figure 5. Results of the FE analyses (N = 20 cycles) with top line displacement of $u_{x,top}$ = ±5, 20, and 40 mm (at 50% translation of the base point): *left column* – settlements u_y of the backfill surface; *middle column* – horizontal stresses σ_x in the winter (W) and summer position (S); *right column* – cyclic evolution of the normalised horizontal force $K_{mob} = 2F_x / (\gamma H^2)$ in the summer positions (Stastny et al., 2025a).

stress peaks at around 2 m height, which intensify with each summer and winter cycle, see Figure 5b. This is attributed to cyclic "overshooting" effects, which are particularly pronounced at larger lateral displacements (i.e. longer bridge lengths). For shorter bridge lengths (e.g. $u_{x,top} = \pm 5$ mm), no overshooting was observed. A more in-depth analysis of the overshooting effects is provided in Stastny et al. (2025a).

Figure 5g presents the evolution of the normalised horizontal earth pressure $K_{mob} = 2F_x / (\gamma H^2)$ in successive summer phases for all considered superstructure displacements $u_{x,top}$ = ±5, 20, 40 mm. As expected, for all constitutive models, the mobilised earth pressures increase significantly with horizontal displacement $u_{x,top}$ and thus with superstructure length. Qualitatively comparable cyclic increases of earth pressure are observed; however, different trends and quantitative deviations occur beyond $N > 10$ cycles. All constitutive models show the strongest increase of earth pressure within the first 5 cycles, followed by a gradual decline in the cyclic increment. A similar development is observed in experiments with poorly-graded sands (and pure abutment rotation), cf. (England et al. 2000, Lehane 2011, Havinga et al. 2017, Stastny 2025a). For well-graded gravels and pronounced abutment translation of 50%, no experimental data are available. The upcoming section will show that the considered translation has a significant influence on cyclic earth pressure mobilisation: pure abutment rotation results in much greater cyclic increases compared to the 50% translation considered here (see Figure 6). For DeltaSand, in the present case (with 50% translation), no relevant increase of K_{mob} is observed beyond 10 cycles for any bridge length, see Figure 5g. Only a minor cyclic densification of the backfill can be detected for DeltaSand (similarly to the calculations with Sanisand-MS), resulting in barely any increase of stiffness for $N > 10$ cycles. The strong and continuous growth of K_{mob} for Hypo+IGS is attributable not only to a stiffness increase due to pronounced densification of the backfill (see next paragraph) but also to the overshooting effects, especially for $u_{x,top}$ = ±40 mm. However, Sanisand-MS also shows a comparable cyclic increase – though without identifiable overshooting. For Sanisand-MS, the cyclic "ratcheting" parameters are primarily responsible for the increase of K_{mob}, cf. Stastny et al. (2025a).

The cyclic development of settlements at the backfill surface is shown in Figure 5 (*left column*) exemplarily for $u_{x,top}$ = ±40 mm. All models show increasing settlements with cycle number, although DeltaSand and Sanisand-MS exhibit only small additional settlements after 10 cycles. In contrast, Hypo+IGS shows consistent cyclic "ratcheting" with high settlement accumulation and densification directly behind the abutment. The ratcheting in the Hypo+IGS model can only be controlled to a limited extent. 1*g* and *ng* experiments typically show cyclic settlement increases with a decreasing rate, cf. (England et al. 2000, Lehane 2011, Stastny 2025a). The absolute settlements – e.g. 60 mm for DeltaSand in summer cycle 20 – are too high due to the unrealistically large bridge length (L = 320 m). For shorter bridges (L = 40 and 160 m), more realistic maximum settlements of 6 mm and 26 mm, respectively, were observed after 20 cycles.

Additional investigations with varying abutment deformation patterns show that the horizontal earth pressure and its cyclic increase during summer cycles strongly depend on the translational movement component of the abutment ($u_{x,foot}$), see Figure 6. The FE calculations were carried out using the DeltaSand model (for the backfill) with a displacement of $u_{x,top}$ =

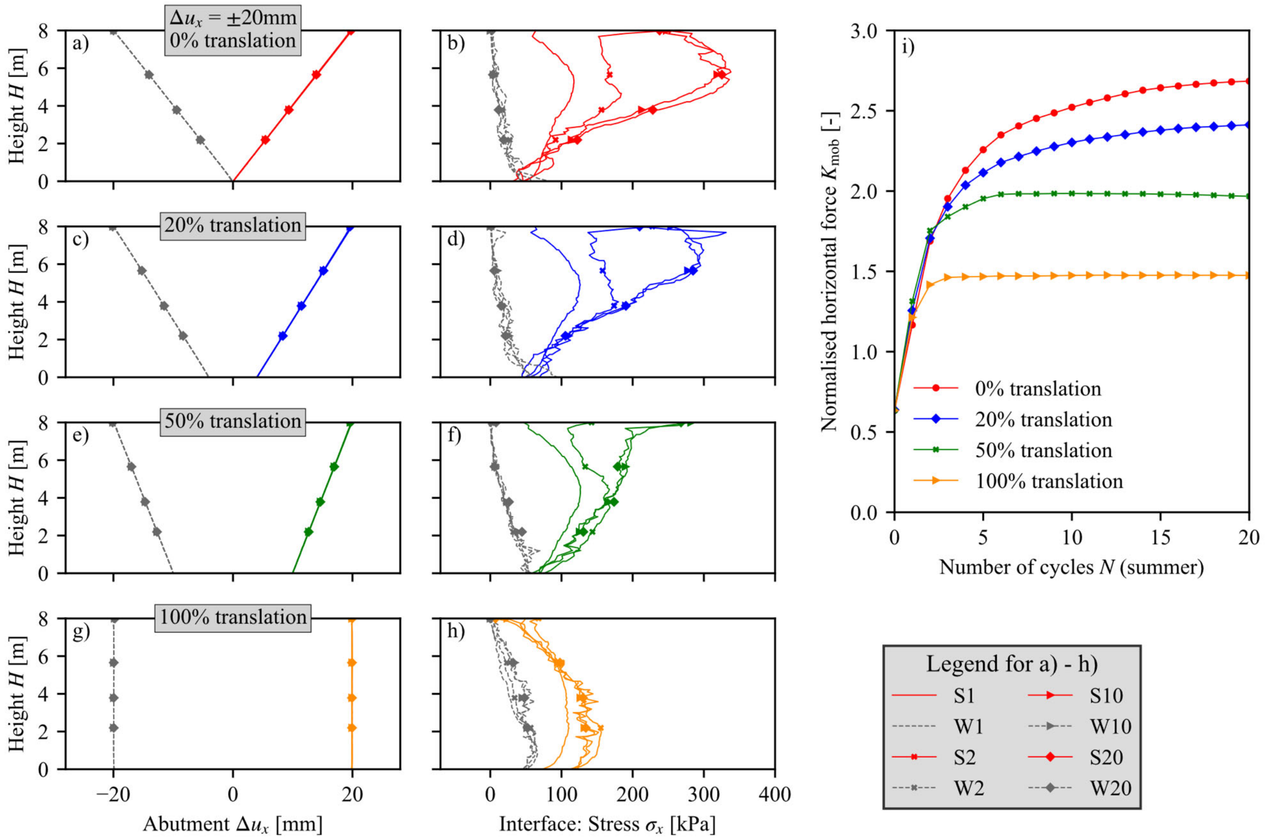

Figure 6. Results of the FE analyses with DeltaSand ($N = 20$ cycles) using line displacement ($u_{\mathrm{x,top}} = \pm 20$ mm) and variation of the foot displacement with 0, 20, 50, 100% translation: *left column* – horizontal displacement u_x of the abutment; *middle column* – horizontal stresses σ_x in the winter (W) and summer position (S); *right column* – cyclic evolution of the normalised horizontal force $K_{mob} = 2F_x / (\gamma H^2)$ in the summer positions (Stastny et al., 2025a).

±20 mm. In this context, the abutment's footing displacement was gradually varied with $u_{\mathrm{x,foot}} = 0, 0.2, 0.5, 1.0\ u_{\mathrm{x,top}}$, see Figure 6 (*left column*). Under pure rotation ($u_{\mathrm{x,foot}} = 0$ mm), the highest earth pressures and the strongest cyclic increase of the mobilisation coefficient K_{mob} were observed, see Figure 6i. In contrast, for a footing displacement of 50 or 100%, no further cyclic increase was observed after more than 10 cycles. Additionally, the computed stress peaks are positioned in the upper part of the abutment for a small foot displacement (Figure 6, *middle column*) while for pure translation the peak stresses manifest in the lower part of the abutment, see Figure 6h. This indicates that the cyclic mobilisation of earth pressure significantly depends on the actual displacement of the entire abutment. A realistic representation of this movement is crucial for structural design. The frequently assumed pure rotation of the abutment in numerical analyses and experiments may therefore lead to an overestimation of K_{mob} and its cyclic increase.

6 CONCLUSIONS

In this contribution, four constitutive models under cyclic loading – Hypo+IGS, Hypo+ISA, DeltaSand, and Sanisand-MS – were calibrated and compared using laboratory test data for highly compacted, well-graded gravel backfill. All models were able to adequately represent the cyclic behaviour and stiffness of the soil but exhibited varying degrees of over- and undershooting effects during repeated unloading and reloading cycles. DeltaSand showed the greatest robustness against overshooting effects, while Hypo+ISA appeared particularly susceptible in the present case.

In boundary value problem studies on the cyclic soil-structure interaction (SSI) of integral bridges, the constitutive models (Hypo+IGS, DeltaSand, Sanisand-MS) displayed qualitatively similar cyclic developments of earth pressure distributions for different bridge lengths. However, compared to the other models, Hypo+IGS showed an unrestrained cyclic accumulation of settlements ("ratcheting"). Additionally, pronounced overshooting effects were observed with this model in the case of longer bridges, which could lead to a greater cyclic increase of earth pressure. The study highlights the importance of careful calibration and verification of the suitability of constitutive models – both at the element test level and in boundary value problems. Further research is needed to improve constitutive models, particularly with regard to overshooting effects. Potentially, some recent improvements of the Hypo+IGS formulation with regard to overshooting effects, such as by Alipour and Wu (2023), Mugele et al. (2024) and Tafili et al. (2024) may already prevent some relevant over- and undershooting phenomena.

Complementary studies show that the deformation at the foot of the abutment has a significant influence on the mobilisation of passive earth pressure and its cyclic increase. Additional practice-oriented research results on the cyclic SSI of integral (railway) bridges are presented in Stastny et al. (2025b, 2025c).

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