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In-situ small strain stiffness measurements of deep soil mixing with PS-logging

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ABSTRACT: Sweden is planning several new railway lines, including the East Link between Järna and Linköping and the Gothenburg-Borås line. Some of these new tracks will be built in areas with soft clay soil susceptible to settlements and vibrations. To achieve the required track stiffness and stability, the mechanical properties of the soft natural clay must be improved, typically through deep soil mixing (DSM). However, this type of stabilization substantially increases the carbon footprint of railway construction, and cost reduction remains a key objective. Therefore, an ongoing effort is being made to optimize the design by reducing the binder amount while maintaining a robust and sustainable solution. Optimization of foundation design is urgently needed but is currently limited by design tools that have not yet been validated for train speeds above 200 km/h, and by the difficulty of obtaining high-quality measurements of the highly variable in-situ properties of clay improved with dry deep soil mixing. The in-situ *PS-logging* method for measuring the stiffness of deep-mixed clay in existing track foundations was evaluated to support planning of future field tests with high-speed trains in Sweden, and potentially in other regions with soft or quick clay conditions. The measured shear wave speeds in the stabilized soil ranged from 220 to 600 m/s, meaning a stiffness variation with a factor of about 10. Interpretation of the field measurements, combined with numerical analyses, suggests that the method can provide useful results, although further work is needed to improve data quality. The numerical analyses also helped identify an appropriate range of vibration frequencies for achieving accurate shear-wave velocity measurements.

KEYWORDS: Deep soil mixing, in-situ small strain stiffness, PS-logging, numerical analysis.

1 INTRODUCTION

Significant demand exists to increase train speeds and loads, to maintain existing lines efficiently, and ensure reliable design for new railways (Dehlbom 2018; UIC 2024). Sweden is building new lines such as the East Link, Gothenburg–Borås, and Norrbotnia, some crossing soft clay areas prone to settlement and vibrations. To meet stiffness and stability criteria, these soils require improvement, commonly via deep soil mixing (DSM) with lime and/or cement. DSM reduces settlements, improves stability, and limits vibrations; it was used successfully at Ledsgård in the 1990s to address ground vibration boom (Holm et al. 2002). However, design tools are not validated for speeds above 200 km/h, and in-situ property measurements remain challenging. This knowledge gap motivates new field tests at higher train speeds.

Ground improvements must satisfy settlement and dynamic response criteria to avoid costly maintenance. Track irregularities increase wheel loads and rail damage (Holm et al. 2002, Nielsen 2018, Dehlbom 2018, Nasrollahi et al. 2023). Higher loads may amplify cyclic subsoil stresses, requiring control to prevent further settlement. For high-speed trains, operational speeds must remain well below the track system's critical velocity (Krylov 2017, Madshus and Kaynia 2000). Evaluating speed and weight upgrades to existing lines demands better understanding of long-term cyclic behaviour (Gebretsadik 2014) and variability in stabilized soil properties (Wong et al. 2024).

DSM can account for up to one third of a railway project's CO_2 footprint (Caspersson 2021), mainly due to cement-based binders. Reducing binder use requires optimized design balancing settlement and dynamic stiffness. This calls for further research and specialist education within 1) site and laboratory characterization of stiffness and long-term DSM behaviour, 2) characterization and modelling of static and dynamic loads, 3) construction and quality control for achieving target properties.

Advanced numerical models exist for static loads (e.g. Bozkurt 2023) and initial dynamic studies (Hall et al. 2022; Hååard et al. 2024) but rarely address the behaviour of different patterns of DSM columns (Müller et al. 2020). Reliable in-situ stiffness data are essential for model calibration (Larsson 2021). Evaluating old DSM columns may also be necessary (Löfroth 2005). No standardized methods exist for in-situ stiffness testing (Helle et al. 2022; Dannewitz et al. 2005), and property variability is high (Larsson et al. 2005; Wong et al. 2024); e.g., strength estimated by column penetration tests can vary by a factor of three within one column.

These gaps justify new field tests of high-speed (>250 km/h) railway lines at well-characterized sites to improve design tools and regulations. Previous tests (e.g., Ledsgård, Holm 2002; Svealand, Dehlbom 2018; Gröna Tåget at Skövde, Västerås, Bjästa) lacked subgrade dynamic measurements. Future tests require robust geotechnical characterization and methods to assess dynamic properties of individual DSM columns, as stiffness variability strongly influences track performance.

The aim of this study, part of a Swedish Transport Administration project on vibrations from railway embankments, was to improve design and construction methods by understanding in-situ properties of DSM improved soil, their age-related variation, and their link to dynamic and long-term track behaviour. The objectives were 1) select a geophysical method for measuring stiffness (wave speed) in existing DSM columns through pilot field tests and 2) identify signal processing and numerical modelling approaches needed to interpret the measurements. Field measurements at Høvik, Norway using PS-logging for the first time in the dry-method DSM stabilized clay and seismic wave modelling to assess stiffness in DSM improved and natural clay are described below.

2 SELECTION OF MEASUREMENT METHOD

A brief literature review was conducted to identify suitable methods for evaluating the stiffness of existing DSM columns. Traditional in-situ strength and stiffness assessments for quality control often rely on penetration-based methods such as FOPS (preinstalled reverse pile sounding), (F)KPS (predrilled pile sounding or column penetration test), and CPT (Cone Penetration Test) (Helle et al., 2022; Kozubal et al., 2023), as well as sampling and visual inspection. These methods can yield inconsistent results, and strength variability is often large. Therefore, it is recommended to evaluate column quality and homogeneity with a combination of the methods.

Seismic techniques for measuring wave speed in concrete have been established for decades (ASTM, 2020; Naik and Malhotra, 1991) and have been adapted for stabilized clay (Hov et al., 2023; Kozubal et al., 2023; Lin et al., 2012; Lindh and Lemenkova, 2023; Ryden et al., 2006; Åhnberg and Holmén, 2011). These studies have proposed empirical relationships linking wave speed (or stiffness) to compressive strength. In-situ seismic methods include down-hole techniques (Dannewitz et al., 2005), SCPT, surface wave seismics (Lin et al., 2012), and up-hole logging (Hiraide et al., 1996). Emerging approaches using fibre optic cables (Rossi et al., 2022; Rørstadbotnen et al., 2023; Trafford et al., 2022) are also under development.

Up-hole and down-hole methods allow wave speed measurements from a single borehole, while cross-hole seismics applied in concrete and DSM columns (Helle et al., 2022; Lindh and Lemenkova, 2023; Mattson, 2008) require parallel holes to ensure accurate travel distance. However, due to stiffness variability, wave paths may deviate from straight lines, necessitating numerical modeling for interpretation. Fiber optic methods were excluded for this study because of the complexity of installation. Consequently, PS-logging was selected as the most practical approach, as it can be performed in a single borehole and thus was suitable for this pilot study.

3 PS-LOGGING METHOD

The selected method, P-S logging (or suspension logging), is widely used in projects with strict seismic design requirements, such as offshore construction, and in countries like Japan and the USA, where small-strain soil stiffness characterization is essential. A brief description and literature review of P-S logging are provided below.

P-S logging is an “up-hole” technique using a low-frequency acoustic probe to measure pressure (P) and shear (S) wave velocities via indirect excitation. It enables high-resolution wave speed measurements to depths of up to 1000 m. In this study, a Robertson Geo probe was used. The method measures wave travel times between two receivers in a fluid-filled borehole, excited by a transmitter located below them. Wave propagation depends on frequency content, geometry, and stiffness contrasts in the surrounding media (Wehner et al., 2021; Stevens and Day, 1986). Due to the complex geometry of stabilized soils, numerical modelling is essential for interpreting wave propagation.

The technique is designed for uncased boreholes filled with water or drilling mud but can also be applied to cased boreholes if coupling is adequate. Steel casings often introduce tube waves or interface waves, which travel faster than shear waves and can distort results (Galperin, 1985; Wehner et al., 2021). PVC casings reduce this effect but do not eliminate it, as shown in Section 5. Standing waves in the borehole fluid can also interfere with measurements; these can be mitigated by wrapping bubble plastic around sondes or cables (Matsubara, 2024).

P-S logging originated in Japan in the 1960s (Kitsunezaki, 1968, 1975) and was further developed by Ogura and colleagues (Ogura, 1979, 1980; Tanaka et al., 1986; Kaneko et al., 1990). Today, it is widely used onshore and offshore (Biringen and Davie, 2010), and standardization efforts are ongoing (Hen-Jones, 2024). Several studies have evaluated its performance: Kwong (1998) tested steel-cased boreholes in weathered granite, reporting shear wave speeds of 150–300 m/s. Pérez-Santisteban et al. (2011) applied the method in a railway embankment, finding shear wave speeds up to 50% higher than those from surface wave methods, likely due to casing effects. Similar discrepancies were reported by Sasanakul and Grassman (2019), who observed higher velocities in the upper 15 m of PVC-cased boreholes.

Tube waves, induced by asymmetrical impulses in the borehole fluid, are a known source of error (Lin and Lin, 2016; Hoyle, 1989; Norris, 1990). These waves travel faster than shear waves in soft soils, such as clay or stabilized clay, and can lead to overestimation of stiffness. P-S logging has also been applied to stabilized soils (Hiraide et al., 1996; Porbaha et al., 2012). In these cases, slurry-based DSM method rendering high-strength soil-cement columns, allowing for uncased boreholes, reducing interference. Reported shear wave speeds ranged from 300–1000 m/s, with corresponding unconfined compressive strengths of 1–4 MPa and Poisson’s ratios of 0.3–0.4.

4 FIELD TESTS

4.1 *Test site at E18 Høvik, Norway*

Field tests using P-S logging were carried out at a construction site for the E18 highway at Ramstadsletta in Høvik, Bærum, Norway. The logging was conducted by Robertson Geo in collaboration with NGI, Keller Geoteknikk AS, Skanska, and the Norwegian Public Roads Administration (Statens vegvesen).

The site is underlain by soft and, in places, quick clay over bedrock at 10–25 m depth. To improve stability, block stabilization was implemented using overlapping DSM columns. P-S logging was performed in two boreholes within stabilized soil (B_3080 and B_3147) and one borehole in natural fill/clay.

Unexpected borehole collapses occurred during and after drilling, likely due to the short curing time (~20 days). As a result, measurements were limited to 5.5 m in B_3080 and 3 m in B_3147. To prevent further collapse, plastic casings were installed. However, as discussed above, casings can influence wave speed measurements. Numerical modelling was therefore performed to assess the potential impact of the plastic pipes on the results (section 5).

4.2 *Data analysis*

The description of data collection and processing is limited due to space restraints. PS-logging was performed in three boreholes, recording P-wave (Vp) data on both “Near” and “Far” channels and S-wave (Vs) data from left and right source hits. Measurements were taken at 20 cm intervals from the bottom to the top of each borehole, with depth coverage depending on borehole length and probe size. Vp data were sampled at 2.5 µs intervals over 5 ms, yielding 2048 samples per record.

During processing, it was observed that the presence or absence of an analog filter likely influenced the data. Various digital frequency filters were applied to identify signal frequencies and reduce noise, using bands of 100–1,000 Hz and 1,000–10,000 Hz. P-wave velocities were estimated using a cross-correlation method to determine time delays between

Near and Far receivers. This approach was particularly useful when first-break picking was difficult, likely due to coherent noise.

P-wave velocities in DSM columns appeared to be the most reliable, while S-wave velocities showed greater variability with depth, possibly due to signal interference, electronic issues, or external vibrations from traffic and construction. Variations in soil properties with depth likely also contributed to differences in wave speeds. DSM stabilized clay seems to dampen vibrations more than natural clay, which is beneficial for reducing traffic-induced vibrations but may complicate wave-based testing methods such as PS-logging and cross-hole seismics. Several technical issues were observed during measurements and are described in Johansson et al. (2025).

4.3 *Measurement results*

In the deep-mixed soil, average shear wave velocities were approximately 350 m/s (corresponding to Gmax≈250 MPa) in borehole B_3080 (Figure 1) and 250 m/s (Gmax≈110 MPa) in B_3147 (Figure 2). Wave speeds determined by Robertson Geo and NGI are marked with RG and NGI, respectively. This suggests that the stiffness of DSM stabilized clay is roughly 15–30 times greater than that of the original clay. Some variation with depth was observed, with shear wave speeds ranging from 230–600 m/s in B_3080 and 220–280 m/s in B_3147. These values are broadly similar to those reported in the KlimaGrunn project (Helle et al., 2022) at a nearby site.

Shear wave velocities were estimated for a lower frequency band (approximately 250–1,300 Hz), while P-wave velocities were derived from higher frequencies (>1 kHz). In non-stabilized clay, shear wave speeds were very low, as estimated using empirical methods. The lowest measured speed was about 60–70 m/s, corresponding to a small-strain shear modulus (Gmax) of 7–8 MPa.

PS-logging data indicated shear wave speeds in quick clay of 190–210 m/s (Figure 3), which are much lower than those manually picked by Robertson Geo. In contrast, P-wave speeds compared reasonably well with manual picks. The PS-logging shear wave speeds (Figure 3) were roughly twice as high as those estimated empirically (not shown here). It is likely that the presence of a casing and the influence of tube waves interfered with the interpretation of shear wave speeds in the non-stabilized clay.

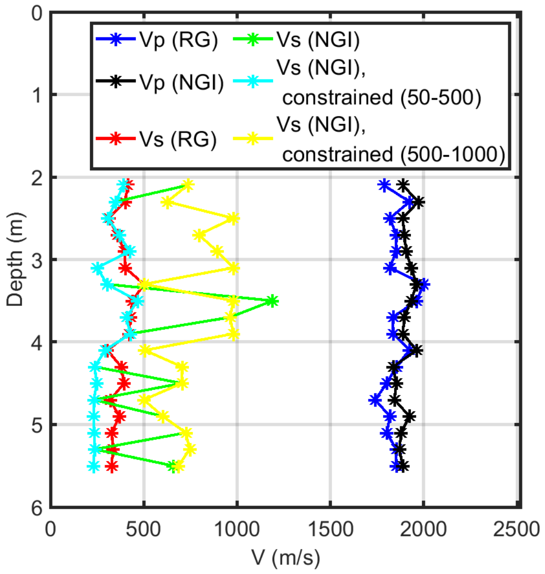

Figure 1. Comparison of Robertson Geo (RG) and NGI wave speed estimates in deep mixed soil for B_3080 without the analogue filter.

5 NUMERICAL AND ANALYTICAL ANALYSIS OF PS-LOGGING

To support the interpretation of PS-logging data, numerical simulations were performed of elastic wave propagation along a PS-logging tool in a borehole within a DSM column. The objectives were to improve understanding of wave propagation in a fluid-filled borehole within DSM, and how the wave velocity of the surrounding DSM material should be estimated.

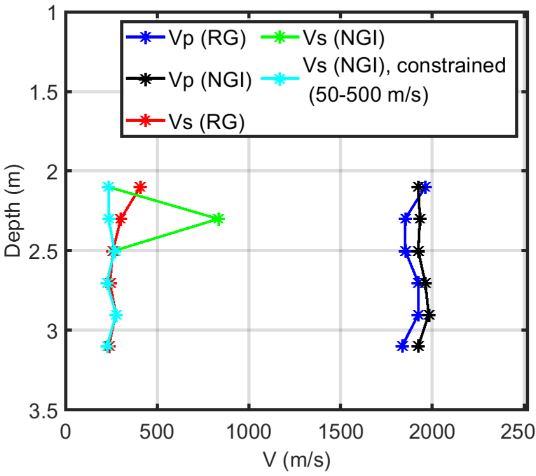

Figure 2. Cross correlation results on filtered Vs data for B_3147 and a summary of Vp and Vs data for B_3147

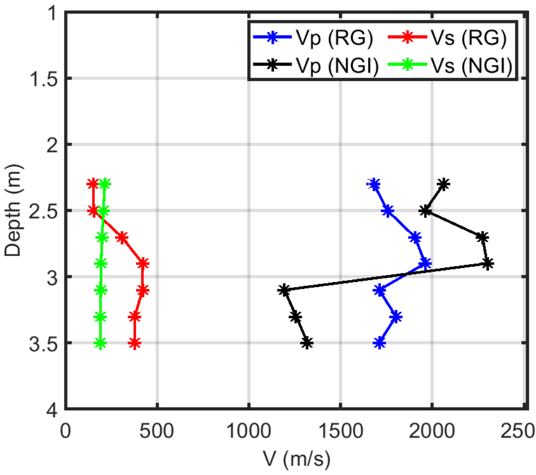

Figure 3. Comparison of NGI velocities and Robertson Geo handpicked velocities in quick clay

The influence of polypropylene (PP) casing on seismic waveforms and the variation of estimated (phase) velocity with pulse frequency was also investigated. The primary goal of the numerical analysis was to model wave propagation during PS-logging and assess how interpreted wave speeds relate to the actual input velocities. Both 2D axisymmetric and 3D finite element analyses were carried out.

5.1 *Effect of plastic casing on wave pattern and interpreted shear wave speed*

As described earlier, the boreholes in both stabilized and non-stabilized soil collapsed, so polypropylene (PP) casing was installed during field testing. Unexpectedly high shear wave velocities were measured in the non-stabilized soil in this study, as well as in some previous PS-logging studies. To investigate how the PP casing may have influenced the field measurements, frequency domain numerical simulations with and without casing were performed using the COMSOL Multiphysics finite element software. Key model parameters used for the materials in the simulations are provided in Table 1.

Table 1. Model parameters in numerical simulations.

Parameter	Clay	DSM	Poly-propylene casing
Shear wave speed (m/s)	100	300	1000
Pressure wave speed (m/s)	1005	561	2400
Density (kg/m3)	1800	1900	500
Material damping (%)	5	1 or 10	0
Poisson's ratio	0.495	0.3	~0.4

Figure 4 presents numerical results for a vibration frequency of 300 Hz with a pressure source placed symmetrically in the lower-left corner of a quarter 3D model representing a water-filled borehole in homogeneous clay. Absorbing boundaries were applied on the right side and top of the model to minimize wave reflections. A clear difference in wave patterns is observed with and without the plastic casing: the casing appears to increase wave speed, resulting in a longer wavelength, and produces a pattern around the borehole resembling the wake of a boat in water. The casing also seems to reduce the amplitude of the induced wave signal and introduce greater damping as the wave propagates upward.

When the pressure source was replaced by a symmetrically placed shear wave source (not shown), the casing caused no significant change in shear wave speed, although it increased damping (attenuation). A similar increase in damping was also noted when using a pressure source in the numerical analysis.

As discussed in section 3, achieving a perfectly symmetrical source placement in the field is challenging, which likely results in a mixture of wave patterns. This complexity can make it difficult to interpret accurate shear wave speeds when a casing is present, particularly in softer soils with shear wave speeds below approximately 200 m/s.

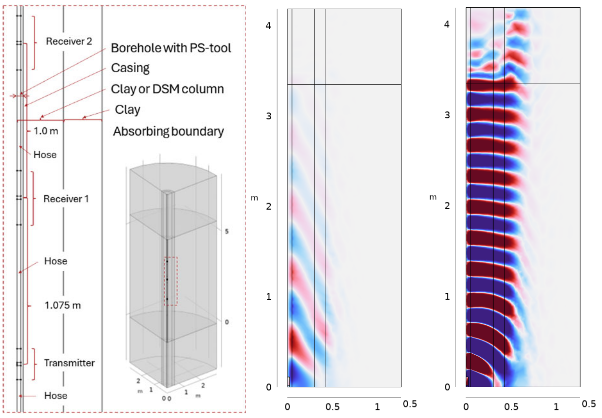

Figure 4. Effect of PP-casing on the wave pattern for a pressure-source vibrating with 300 Hz in a borehole in homogenous clay (no lime cement). Left: Model geometry, middle: results with casing and right: results without casing. The pressure source is located at origo in color plots, and the waves are travelling from the bottom and upwards.

5.2 *Interpreting shear wave speeds*

Figure 5 shows interpreted shear wave speeds from a numerical model using a symmetrically placed shear wave source in a water-filled borehole with PP casing inside a DSM column surrounded by clay. Wave speeds were estimated for vibration frequencies between 100 and 1,000 Hz. At lower frequencies, the longer wavelengths penetrated into the surrounding soft clay, reducing the computed phase velocity. As frequency increased (up to ~600 Hz), wavelengths shortened, and the computed phase velocity approached the DSM shear wave speed of 300 m/s. For frequencies above 700 Hz, additional wave modes were likely induced, causing phase velocities to rise toward 1,000 m/s—exceeding the P-wave speed of the DSM (~560 m/s). These results indicate that interpreted velocities are influenced by a combination of fluid wave speed, P-wave speed in the DSM material, and the surrounding clay.

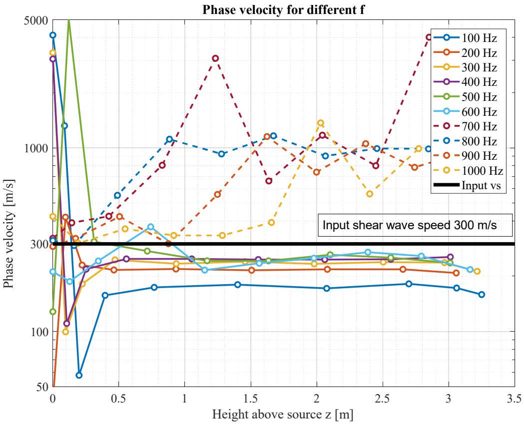

Figure 5. Phase velocities varying with elevation above transmitter for shear (dipole) source in a fluid filled bore hole with PP-casing in a lime cement column with a shear wave speed 300 m/s in clay deposit with a shear wave speed of 100 m/s. Transmitter at z=0.

5.3 *Analytical tube wave speeds*

Ideally, P-S logging should primarily generate flexural or shear waves. However, as noted earlier, the source mechanics and its asymmetrical placement in the borehole may also induce tube waves. To better understand whether and how casing might have affected the field measurements, tube wave speeds were estimated using the equations provided by Wehner et al. (2021) following Norris (1990).

Similar to the field conditions, the analysis considered a 75 mm diameter borehole, both with and without a 2.5 mm thick polypropylene (PP) casing. The equations account for the logging tool, whose stiffness is uncertain because it includes both rigid components (e.g., transmitter, receivers, analog filter) and flexible elements (e.g., rubber hose with wiring). Therefore, tube wave speeds were evaluated as a function of soil shear wave speed for several assumed tool shear modulus values, Gt, ranging from 10 MPa to 10 GPa (Figure 6 and Figure 7). For reference, steel has a shear modulus of about 78 GPa.

The analytical results indicate that tube wave speeds exceed the surrounding soil's shear wave speed when Vs < 300 m/s. Consequently, in soft soils with casing, shear wave speeds measured in the field are likely overestimated—potentially by 50–100%, with greater overestimation in softer soils. For stabilized clay (Vs > 200 m/s) and a 75 mm diameter PP casing, the error is expected to be smaller, perhaps around 30% or less. However, increasing borehole diameter amplifies the effect: for a 150 mm cased borehole and a tool stiffness of 1 GPa, the analytical tube wave speed remains higher than the soil shear wave speed even for Vs up to 700 m/s.

6 STRENGTH ESTIMATES BASED ON WAVE SPEEDS

Although shear wave speeds in stabilized clay showed variability due to several uncertainties, strength estimates were derived using empirical relationships for comparison with laboratory results (Figure 8). Two equations were applied: one by Dannewitz et al. (2005), relating shear wave speed to strength, and another by Larsson and Mulabdic (1991), linking shear modulus to strength. While the latter was developed for non-stabilized clays, it agrees well with lab results for stabilized clay in Sweden (Åhnberg & Holmén, 2008). Shear modulus was calculated from measured wave speeds and used in the Larsson and Mulabdic equation. The variation in wave speeds is reflected in the spread of estimated strengths. Strengths derived from field measurements after 20 days of curing are comparable to lab results at 7 and 28 days, though the highest estimates are 2–3 times greater. Dannewitz's equation yields higher strength estimates. Further research is needed to establish reliable correlations for stabilized clays in Scandinavia, ideally through project- or site-specific calibration due to the many influencing factors.

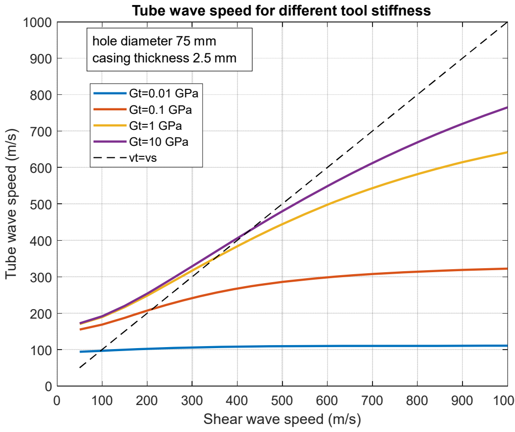

Figure 6. Tube wave speed versus shear wave speed for borehole with casing and with tool inside.

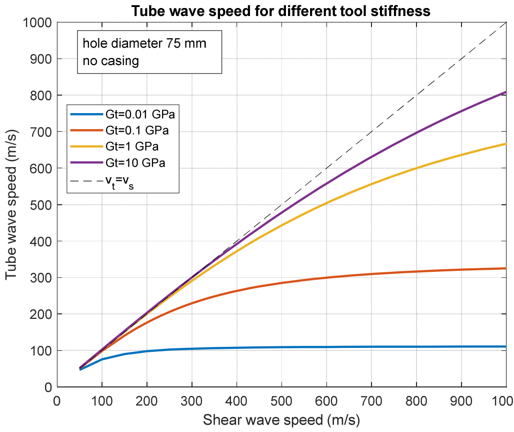

Figure 7. Tube wave speed versus shear wave speed for borehole without casing, but with tool inside.

7 CONCLUSIONS

Sweden's high-speed rail expansion and CO₂ reduction goals demand optimized design supported by validated models and reliable field data. This pilot study advances geotechnical engineering by evaluating PS-logging for in-situ stiffness measurements of DSM stabilized soil columns through field tests and numerical modeling. The following conclusions and recommendations are given.

PS-logging can be a valuable tool for estimating shear wave velocity in soils stabilized with deep soil mixing or jet-grout, offering potential for geotechnical site characterization. However, care must be taken when interpreting results, particularly in non-stabilized soft clay, where overestimation may occur due to tube waves or higher-order wave modes. Accurate application and critical assessment of the data are essential to ensure reliable inputs for design and analysis.

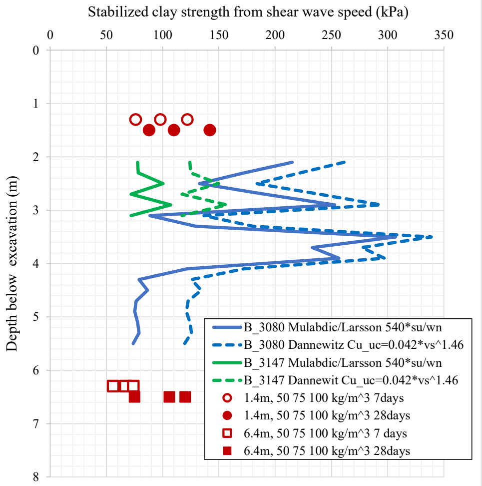

Figure 8. Strength of stabilized clay based empirical equation and measured shear wave speeds in boreholes B_3080 (blue) and B_3147 (green) compared with laboratory evaluated strengths from unconfined compression tests for different amount of cement (50, 75, and 100 kg/m^3) and curing time.

Measurements should be performed under well-controlled conditions, ideally in uncased boreholes after sufficient curing time, to minimize borehole collapse and interference. Frequency filtering between 200–600 Hz is likely necessary to reduce the influence of non-shear wave modes and obtain more reliable shear wave speed estimates.

A well calibrated numerical modeling is essential for interpretation. Numerical simulations confirm that polypropylene casing increases attenuation and can affect signal interpretation, especially in soft soils. Similarly, as for other in-situ methods, site-specific correlations between wave speed and strength, combined with numerical analysis, are necessary for accurate interpretation of PS-logging data.

Additional field measurements with improved equipment, such as stronger sources and multi-receiver tools, are needed to enhance data quality and reduce uncertainties. Building a robust database of field and laboratory results will support the development of reliable design tools and procedures.

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