Proceedings of the 8th International Conference on Civil Structural and Transportation Engineering (ICCSTE'23)
Ottawa, Canada – June 04-06, 2023
Paper No. 209
DOI: 10.11159/iccste23.209

Enhancing the Performance of Railway Trackbed with Vibro Stone Column Technique

Koohyar Faizi[1], John Allsop[2], Paul Beetham[3], and Rolands Kromanis[4]
Koohyar.Faizi@ntu.ac.uk; John.Allsop@van-elle.co.uk; Paul.Beetham@ntu.ac.uk; r.kromanis@utwente.nl
[1,3]Nottingham Trent University
50 Shakespeare St, Nottingham, UK
[2]Van Elle Ltd.
Kirkby in Ashfield, Nottingham, UK
[4]University of Twente
Drienerlolaan 5, 7522 NB Enschede, Netherlands

Abstract **-** The vibro stone column (VSC) technique is a ground improvement method used to enhance the load-bearing capacity. This paper provides an overview of the VSC technique and its application in railway trackbed stabilization (TBS). The VSC technique involves installing columns of good quality stone into the soil using a vibrating probe, creating both a strong column and radial stiffening of the adjacent compressed soil; a composite ground improvement system. The paper discusses the benefits of the VSC technique, such as its efficiency, versatility, and cost-effectiveness, and its limitations in TBS. Additionally, the paper presents the results of a site trial that utilized a vision-based monitoring system to measure the effectiveness of the VSC technique in improving the trackbed stiffness. The results demonstrated that the VSC technique can be considered a reliable TBS system to improve the stiffness of subgrade and sub-ballast layers in railway trackbeds, reducing the risk of trackbed settlement and extending the life of the track. The paper concludes by summarizing the importance of VSC in railway TBS and highlighting its potential for future ground improvement projects. The use of a vision-based monitoring system further enhances the effectiveness of the VSC technique, providing real-time monitoring and analysis of trackbed conditions, enabling better decision-making and improving the accuracy, reliability, and efficiency of the TBS technique.

Keywords**:** vibro stone column, trackbed stabilization, vision-based monitoring system, stiffness

1. Introduction

Ballasted railway tracks built on soft subgrades can experience significant ground deformations during train passage, leading to rapid track deterioration and an increased risk of derailment [1]. Poor subgrade soil can also reduce trackbed stiffness, resulting in geometry defects that require maintenance activities such as automated tamping or manual packing. However, these interventions can disrupt the load-bearing structure and shorten the time between maintenance interventions, ultimately leading to complete track-bed renewal which is highly disruptive and expensive. Low stiffness values can cause high rail deflections and rapid deterioration, particularly at rail joints, which are regarded as weak points in the rail industry due to their higher maintenance requirements and failure rates. Therefore, improving and regulating diminished track stiffness is crucial, and excessive rates of stiffness change should be avoided to ensure safe and long-lasting trackbeds.

Trackbed Stabilisation (TBS) is a remediation used when tracks must be, or have been constructed over soft subgrade with a poor load-bearing capacity. Various TBS methods are proposed for these projects, including mass stabilization with dry deep soil mixing (cement columns) [2], micro-piling [3,4], geogrids [5], and excavate /replacement works. However, some of these treatments, such as geogrids and excavate/replacement, are undesirable for pre-existing rail, as they require removal of the track structure and high cost burdens for the railway operator. Therefore, it is highly desirable to apply a TBS technique with minimum traffic disruption since the financial and operational impacts of track closure increase substantially over time.

Vibro Stone Columns (VSCs), also known as vibro-replacement with stone columns, offer an economical and sustainable alternative to other trackbed stabilization solutions by densifying and strengthening weak or poorly compacted subsoil without removing the track. VSC is a subgrade improvement method in which large-sized columns of coarse aggregate or recycled ballast are installed in the soil by means of a vibrating mandrel. The stone columns and the intervening soft soils form an integrated trackbed support system having low compressibility and reduce the vertical deflection of the track.

Although previous studies have shown the effectiveness of VSC in increasing the embankment stiffness [6], it is unclear whether it provides the same benefits as a full trackbed replacement or other traditional subgrade improvement technique when used for existing trackbed. This paper provides a case study of how VSC may be implemented in the TBS of a pre-existing railway. It also discusses the use of a non-contact measurement system that was adopted to capture the vertical deflection of the rail and estimate the trackbed stiffness before and after VSC stabilization.

2. Methodology

2.1.Vibro-replacement with stone column

Top feed stone columns are recommended as a vibro replacement technique for treating a wide range of soft cohesive , or low stiffness granular soil especially where the ground water table is unlikely to be encountered. They are designed to form reinforcing elements of low compressibility and high shear strength and also impart a radial compression/consolidating effect on the surrounding soil. To test the effectiveness of this technique in a rail trackbed, vibro replacement tests were conducted on a full-size outdoor railway test track at Van Elle's premises in Nottingham. The test track consisted of a 100m long by 5m wide area of jointed rail supported by concrete sleepers with typical sleeper spacing of 0.60m, on 350mm deep ballast. The ballast was underlain by a 1.7m thick layer of ashy Made Ground (MG) material overlying Sandstone. The VSC installation pattern and the process used in the trial are shown in Fig. 1.

In the trial, a top feed vibrating technique was used. A vibrating poker with about 30cm in diameter, known as a vibroflot, was fitted to a purpose-built vibro-piling rig and used to penetrate by compressing the ground radially. The penetration was achieved using the vibroflot's own mass, the pull-down facility of the rig (when used), alongside pressurized air flushes. This created a void, which was filled with granular material (ballast size) followed by compaction of the same. This was achieved via an up and down motion of the vibrator in order to laterally displace the stone into the ground and at the same time compact the stone column. The resulting effect is one of an increased track bed stiffness as was proven by the monitoring (described below).

In the first stage of the trial, one stone column (No.1 in Fig. 1) with a diameter of 300mm was installed between two sleepers at a rail joint and to full depth of the MG. The joint was common to that seen in the UK rail network, where adjoining rail lengths are connected using two metal joint bars, commonly referred to as fishplates, bolted to both ends of rail. The location of the VSC was chosen to investigate the impact of remediation on the vertical deflection of the fishplate as suspected weak points. In a second stage 2 more VSCs were added adjacent to the first VSC and outside the rail four foot, plus 1 further VSC between sleepers, one sleeper away from the fishplate (No. 2 in Fig. 1).

Vertical track deflection measurements may provide an indication of track improvement, but quantifying the improvement in terms of increased subgrade stiffness can be challenging. Therefore, utilizing a method to calculate a localized measure of track quality before and after the stabilization of a site can be beneficial in determining and comparing the effectiveness of VSC and was achieved in this case with the below described method.

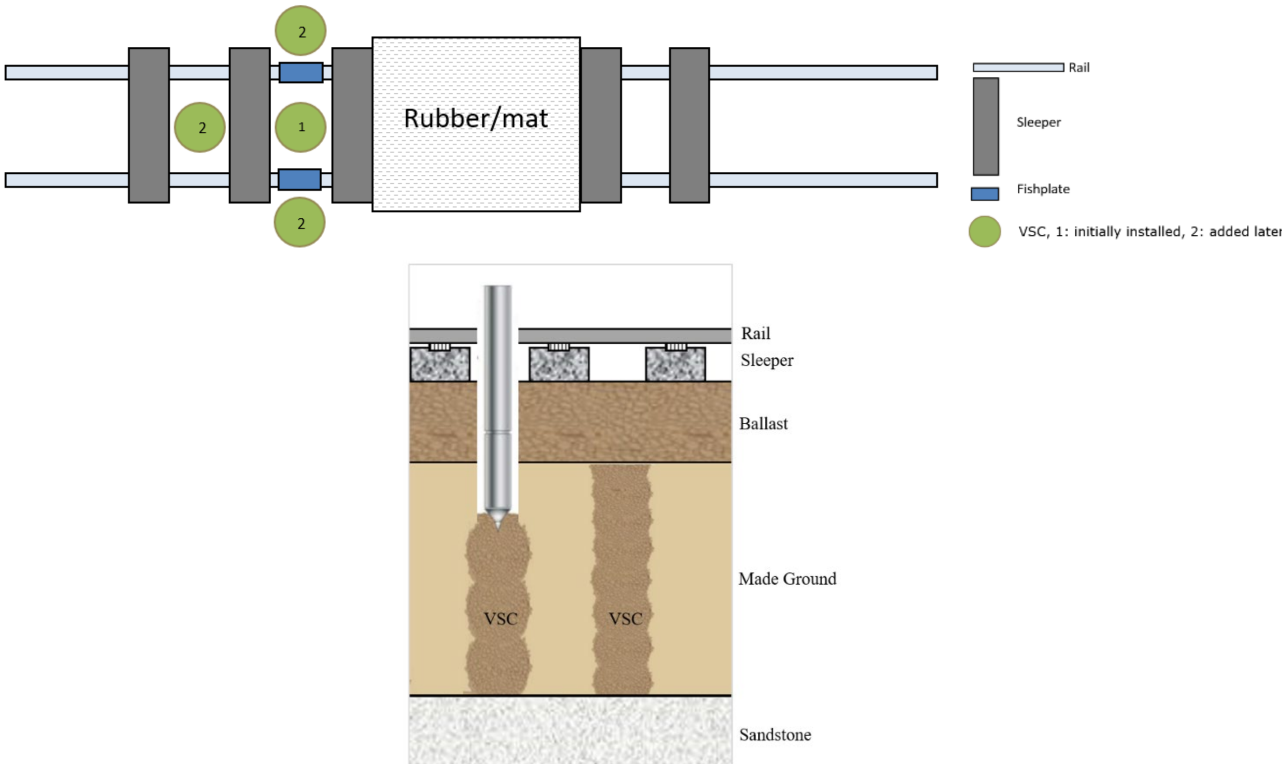

Fig. 1: Schematic of dry vibro-replacement method for stabilizing trackbeds with stone columns; plan view (top) and section view (bottom).

2.2.Vision-based displacement monitoring systems:

Vision-based systems offer many advantages over traditional displacement sensors in civil structures, including lower instrumentation cost, easier installation, and greater measurement capacity in terms of frequency range and spatial resolution [7]. To use a vision-based system for track deflection monitoring, a stable camera is set up to look at targets attached to the track components (rails and sleepers), and the structural displacement is derived through target tracking.

In this study, a computer vision algorithm was used to collect video frames of a predefined region of interest captured by a digital camera. Artificial planar targets were used to measure the displacement of railway track components, with vertical displacement of the rail and sleeper measured by tracking the attached targets. The system used a modified GoPro camera with a zoom lens, set up 2-3.5m from the monitoring location and recording at 120 Hz. The camera was fixed to the ground to minimize vibrations caused by traffic and wind during testing.

The trials continued with monitoring the vertical deflection of the fishplate joint under loading by a two-axle rail vehicle (34 tons COLMAR Railroad loader). The impact of VSC on the deduction of deflection of the rail at the fishplate and sleeper was investigated using VBM (Fig. 2). However, since the experimental data contained unwanted noise caused by passing vehicles on the track, a Butterworth low-pass filter was designed to clean up the signal. Therefore, the results presented for VSC are based on the filtered data.

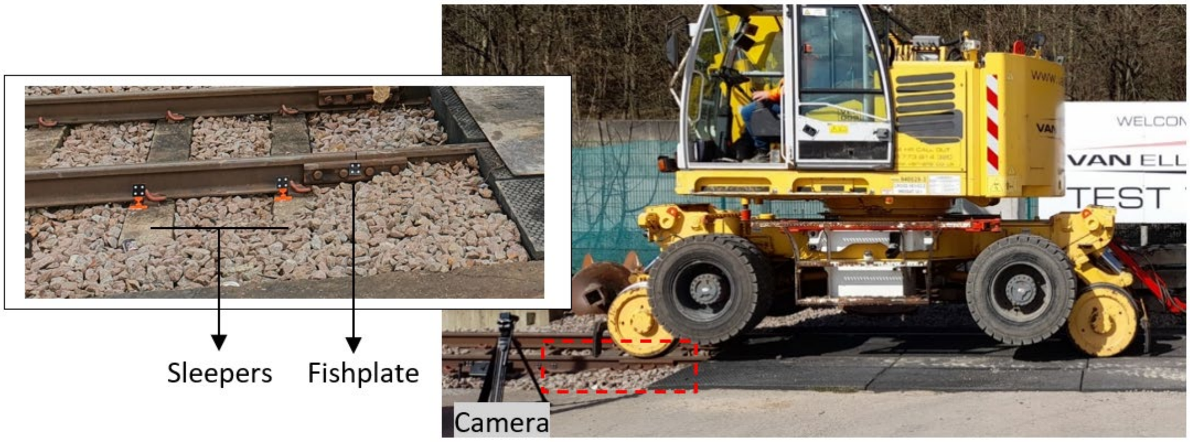

Fig. 2. Trial set-up for VBM.

2.3.The track modulus:

The track modulus is a basic parameter used to measure of track quality, which is defined as the supporting force per unit length of the rail per unit deflection [8] and is a function of both the load applied to the rail and the associated track displacement.

The track modulus was estimated in this paper using the beam on an elastic foundation (BOEF) model. The BOEF is a very prevalent and simple numerical mode for the displacement of a railway track [9]. The most common theory for a BOEF modelling is the Winkler approach.

The differential equation for a BOEF analysis is derived with the vertical deflection of the rail w at distance x along a beam with bending stiffness EI on an elastic foundation with a system support modulus (stiffness per unit length) k :

$$EI + \frac{d^4w(x)}{dx^4} + kw(x) = 0 \tag{1}$$

The vertical deflection of the rail due to a single load P has the solution.

$$\delta(x) = \frac{P}{2k_{sys}L} e^{-(x/L)} \left(cos\frac{x}{L} + sin\frac{x}{L} \right) \tag{2}$$

where L is the characteristic length

$$\delta L = \sqrt[4]{\frac{4EI}{k_{sys}}} \tag{3}$$

Where support system modulus (k_{sys}) is combination of the railpad modulus ($k_{railpad}$) and the trackbed modulus ($k_{trackbed}$), and given by formula for springs in series:

$$\frac{1}{k_{sys}} = \frac{1}{k_{railpad}} + \frac{1}{k_{trackbed}} \tag{4}$$

In this paper, the support system modulus was calculated from the sleeper spacing (s) in the BOEF model the measurements were calculated on the sleeper instead of the rail. The track modulus was also calculated with the rail type UIC 60 based on the displacement at double wheel loads where single load may not be representative of the track response [10].

3. Results and discussion

In this study, VBM was utilized to investigate the reduction in vertical deflection achieved by applying VSC. Figure 3 shows the vertical deflection versus time for the joint, obtained by the VB system, before and after stabilisation. Before stabilisation, the maximum range of negative displacement (downward deflection) at the joint was measured to be approximately 5mm. Whereas, after the installation of 1 VSC and 4 VSCs, the displacement was reduced to approximately 3mm and 2.3mm, respectively (Fig. 3). The tests were repeated by passing the vehicle over the track, and the peaks of upward (positive) and downward (negative)deflections of the rail at the fishplate before and after track stabilisation were plotted in Fig. 4 and Fig. 5. As expected, the installation of additional columns affected the track deflection under loading and resulted in decreased fishplate deflection.

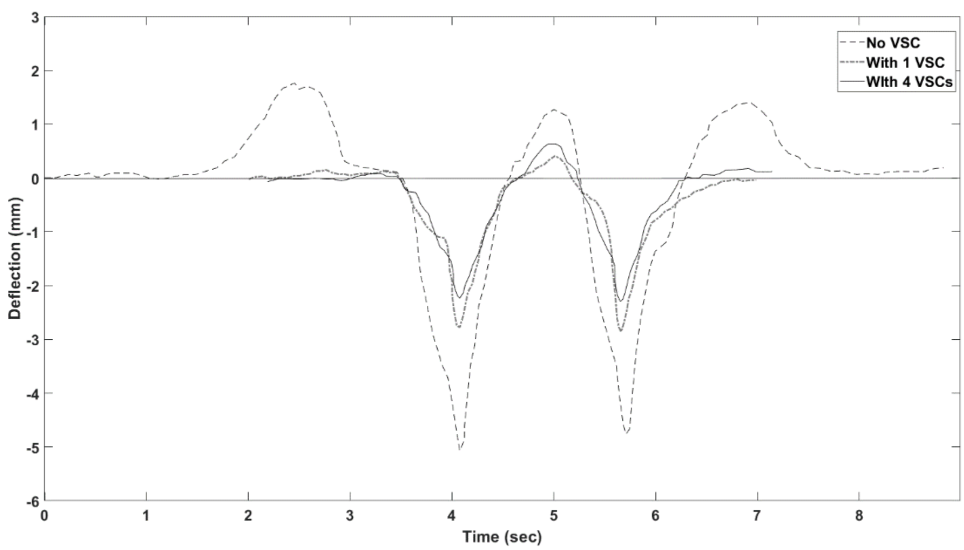

Fig. 3: Vertical deflection of rail at fishplate, obtained by VB system, before VSC, after installation of 1 VSC, and after installation of 4 VSCs.

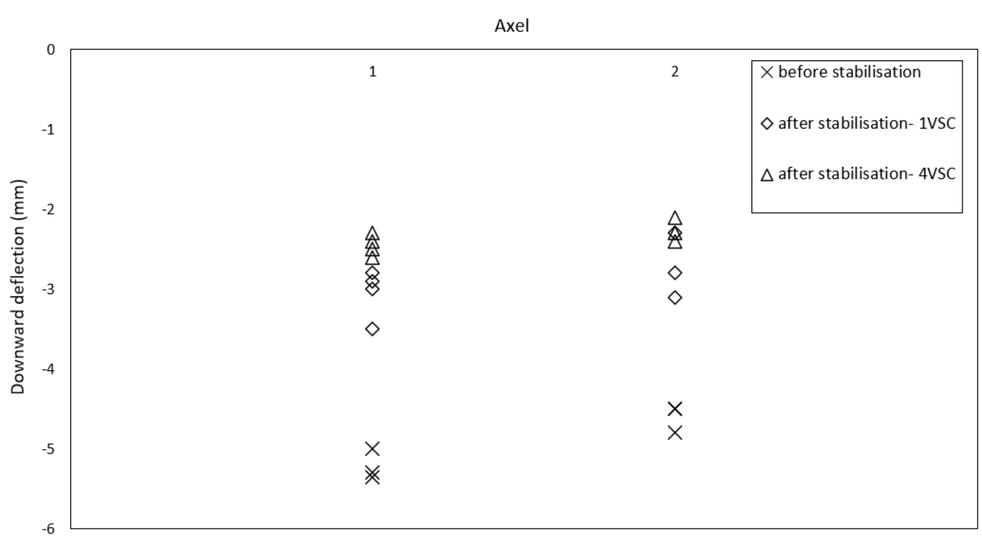

Fig. 4: Maximum downward deflection of the rail at fishplate under repeated vehicle passage load with 34 tones based on various vehicle passage, before and after stabilisation.

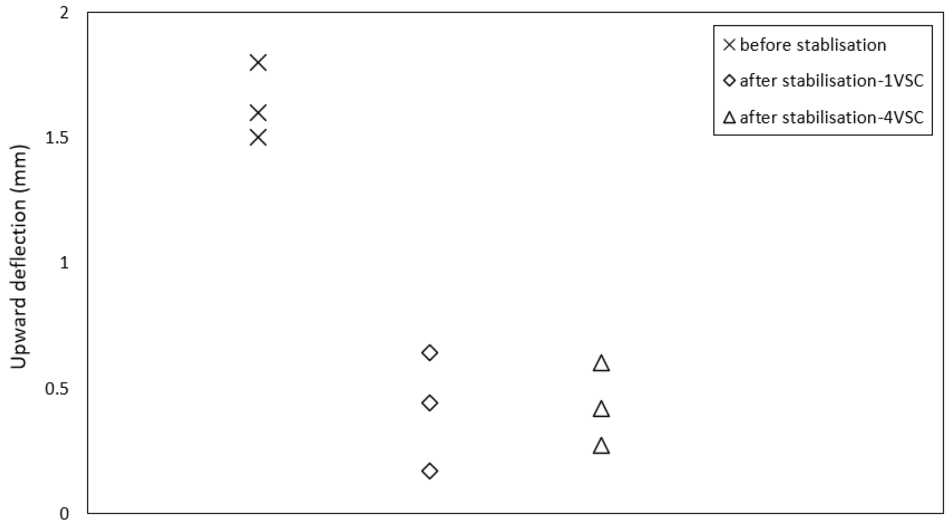

Fig. 5: Maximum upward deflection of the rail at fishplate on repeated vehicle passage, before and after stabilisation.

The vertical displacement of the sleeper was measured by VBM to represent track deflection, and Fig. 6 shows the displacement profiles of the sleeper for the vehicle passage. Comparing the peak displacements after VSC stabilisation (4 VSCs) with the displacements before stabilisation (Fig. 6), it can be seen that the peak-to-peak displacements for the sleeper decreased from approximately 5 to 1.5 mm.

The figures demonstrate that initially the rail experienced positive (upward) displacement due to rail lift-off. However, this upward movement decreased when VSC was applied.

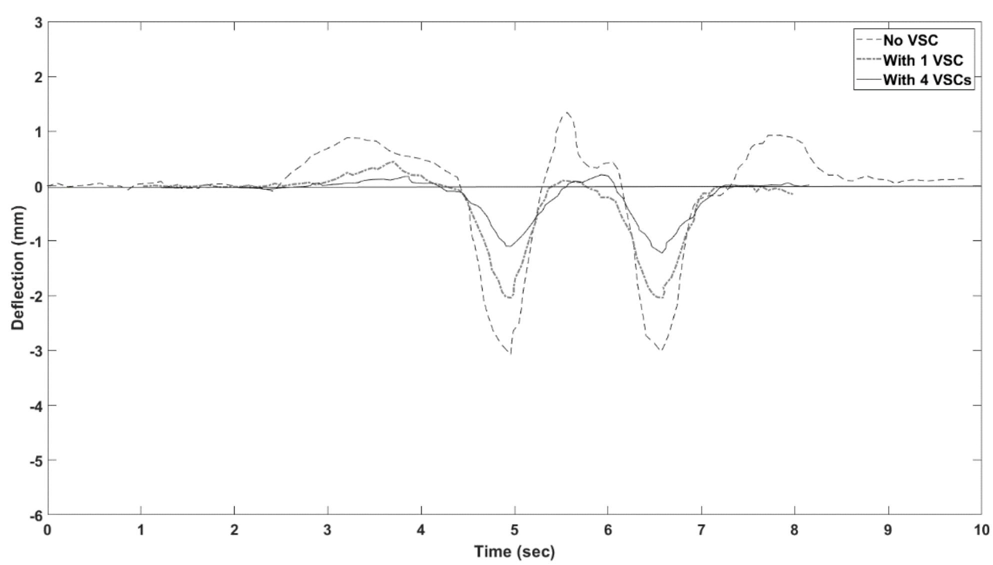

Fig. 6: Vertical deflection of sleeper, obtained by VB system, before VSC, after installation of 1 VSC, and after installation of 4 VSCs.

Figure 7 displays the trackbed modulus calculated at monitoring locations for the vehicle before and after trackbed stabilization using VSC. The values were obtained by plotting the theoretical displacement versus length for a BOEF model and determining the point where the maximum deformation matches the ultimate deformation obtained by VBM. The trackbed modulus increased more than threefold with the installation of 4 VSCs. For comparison, Selig and Li [8] recommended a minimum track modulus of 28 MPa for satisfactory track performance, while Raymond [11] suggested a minimum of 35 MPa.

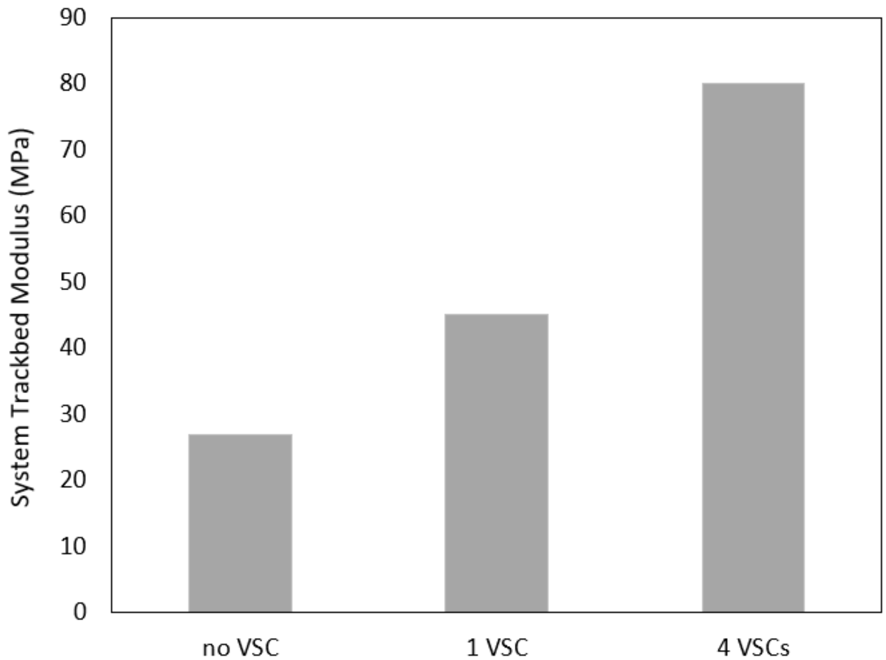

Fig. 7: Comparison of trackbed modulus pre- and post-TBS.

While VSC can be an effective TBS system for improving track quality, the vibrations generated during installation can pose a risk to operations by disrupting equipment or causing movement of the ground or structures, such as settlement or heave. Therefore, careful consideration should be given to the installation of VSCs, especially in close proximity to railway assets like tunnels. Typically, installation methods like driven piling, vibro-compaction, and stone columns are restricted due to excessive vibration. If these methods are used, the developer must demonstrate that the peak particle velocity of vibrations does not exceed 5mm/s at any structure. If this cannot be demonstrated, a settlement and vibration monitoring regime must be put in place [12].

4. Conclusion

A novel method for increasing trackbed stiffness was proposed and evaluated through a field trial. Vibro stone columns (VSCs) were assessed for their effectiveness in stabilizing the trackbed, with vertical deflection of the rail and sleeper measured using a vision-based monitoring system. Measurement of track modulus was used to quantify the effectiveness of VSC stabilization, as it is highly dependent on subgrade conditions. Results showed a significant improvement (1.7 to 3 times) in trackbed quality and stiffness with the use of VSCs. However, further studies are needed to address concerns about vibration and to evaluate the long-term effects of improved trackbed quality achieved through the use of VSCs.

References

[1] Nielsen, J.C.; Li, X. Railway track geometry degradation due to differential settlement of ballast/subgrade–Numerical prediction by an iterative procedure. J. Sound Vib. 2018, 412, 441–456.
[2] Pye, N., O'Brien, A., Essler, R., & Adams, D. (2012). Deep dry soil mixing to stabilize a live railway embankment across Thrandeston Bog Grouting and Deep Mixing 2012 (pp. 543-553).

[3] MUSGRAVE, P., WEHBI, M., JACKSON, L., STEVENSON, A. & O'NEIL, L. 2017. A Guide to Track bed Micro Piling. Network Rail.
[4] Faizi, K., Beetham, P., Kromanis, R. and Allsop, J., Non-Contact Measurement of Vertical Deflections of Rail Trackbeds and Performance Testing of Stabilized Sub-Ballasts Using a Novel Micropiling System. In Geo-Congress 2023 (pp. 539-548).
[5] Ngo, N. T., Indraratna, B., & Rujikiatkamjorn, C. (2017). Stabilization of track substructure with geo-inclusions—experimental evidence and DEM simulation. International Journal of Rail Transportation, 5(2), 63-86.
[6] McCabe, B.A.; Nimmons, G.J.; Egan, D. A review of field performance of stone columns in soft soils. Proc. ICE-Geotech. Eng. 2009, 162, 323–334.
[7] Kromanis, R. and Kripakaran, P., 2021. A multiple camera position approach for accurate displacement measurement using computer vision. Journal of Civil Structural Health Monitoring, 11(3), pp.661-678.
[8] Selig, E. T., and Li, D. (1994). "Track Modulus: Its Meaning and Factors Influencing It." Transportation Research Record, Vol. 1470, pp. 47-54.
[9] Milne, D., Le Pen, L., Watson, G., Thompson, D., Powrie, W., Hayward, M., & Morley, S. (2018). Monitoring and repair of isolated trackbed defects on a ballasted railway. Transportation Geotechnics, 17, 61-68.
[10] Wheeler, L. N., Take, W. A., & Hoult, N. A. (2017). Performance assessment of peat rail subgrade before and after mass stabilization. Canadian Geotechnical Journal, 54(5), 674-689.
[11] Raymond, G.P. 1985. Analysis of track support and determination of track modulus. Transportation Research Record, 1022: 80–90
[12] Network Rail (2020), The Developers Handbook, C-05-OP-32-3001.