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Safe foundations for High-Speed Rail

Abstract: This article outlines the current guidelines for the geotechnical design of High-Speed Rail (HSR). Special attention is given to aspects of dynamic stability of the soil substrate as a new technical challenge. The vibro-replacement technology is indicated as a suitable reinforcement solution that meets the design requirements for railway trackbeds, with technical details of its implementation provided. Examples of the application of gravel columns for conventional railways in Poland and High-Speed Rail outside the country are discussed.

Keywords: High-Speed Rail; Central Communication Port; Geotechnics; Design; Dynamic Stability; Vibro-replacement; Gravel Columns

High-Speed Rail (HSR) is considered a key element of transport infrastructure, having been developed worldwide for many years, while in Poland, this engineering challenge is only just beginning. HSR includes lines allowing speeds of at least 250 km/h, as well as lines built to high-speed standards enabling speeds of 200 km/h. One of the crucial elements in ensuring train traffic safety is the proper preparation of the soil substrate, including specialised geotechnical works.

Currently, HSR is designed based on the technical standards of the Central Communication Port (CPK) [1], applicable to speeds equal to or lower than 350 km/h. These standards must be applied in geotechnical calculations for earth structures, such as verifying the load-bearing capacity of the soil and the stability of slopes and embankments (ultimate limit states), along with an analysis of displacements and deformations (serviceability limit states). The design process itself follows Eurocode standards: PN-EN 1990, PN-EN 1991, and PN-EN 1997, with the basic service life of railway earthworks set at 100 years.

The impact of railway rolling stock in terms of design load is defined in the same manner as for conventional railways. The traffic load according to the LM71 model, in line with PN-EN 1991, is a uniformly distributed load of 3.0 m in width and 6.4 m in length,

positioned 0.7 m below the rail head, with a value of 63 kPa. This is the characteristic vertical load for mainline and first-class railways, for which the dynamic factor no longer applies.

Verification of soil bearing capacity, slope stability, and analysis of displacements and deformations is conducted in the same manner as for conventional railways. However, the threshold values for displacements used to verify serviceability limit states have been defined differently. The fundamental requirement for the trackbed is to ensure its acceptable settlement throughout its operational period, starting from the moment the track structure is completed. Accordingly, permissible post-construction settlement values for HSR trackbeds have been specified.

Tab. 1. Acceptable post-construction settlement values for HSR trackbed

Type of displacement	Ballastless track	Ballasted track
Maximum post-construction settlement S_R	15 mm	50 mm
Maximum inclination angle due to settlement differences	1/1,000	1/1,000 (*)
Predicted post-construction settlement difference between embankment and structure support	20 mm over 20 m distance	20 mm over 20 m distance (*)

(*) The stated value applies to the trackbed regulation/repair period, which is 5 years.

Settlement or unevenness of the trackbed during its operation may necessitate adjustments to track positioning, potentially compromising stability. In the case of ballastless tracks, such settlements may prevent vertical adjustments to track positioning or even cause structural damage to the track system.

A completely new issue in HSR is dynamic stability. Under cyclic loading caused by railway traffic, dynamic effects occur in the soil substrate. Depending on soil conditions, groundwater level, or underground obstacles, multidirectional wave propagation occurs in the soil, with interference and reflections. Vibrations of the track system itself also take place, causing its movement and deformation. The waves propagating in the soil substrate are divided into longitudinal body waves (P-waves – compressional) and transverse body waves (S-waves – shear) as well as surface Rayleigh waves (R-waves). Soil vibrations caused by trains travelling at speeds above 150-160 km/h can lead to a deterioration of its properties, excessive settlement, and even liquefaction. Soils sensitive to vibration include easily displaceable sands with a grain uniformity coefficient below 2.0 and a relative density $ID < 0.5$, cohesive soils with a liquidity index $IL > 0.4$, and organic soils of various types and origins. Soil stability is adversely affected by groundwater saturation, while it is improved by a cover of stronger soil. The dynamic stability of sensitive layers is at risk when train speeds approach the velocity at which surface R-waves propagate (the so-called critical velocity). To prevent adverse effects, it is recommended that the ratio of train speed to wave propagation velocity does not exceed 0.65-0.70. This condition can be met through various geotechnical solutions – from soil improvement through its reinforcement to foundation solutions using piles.

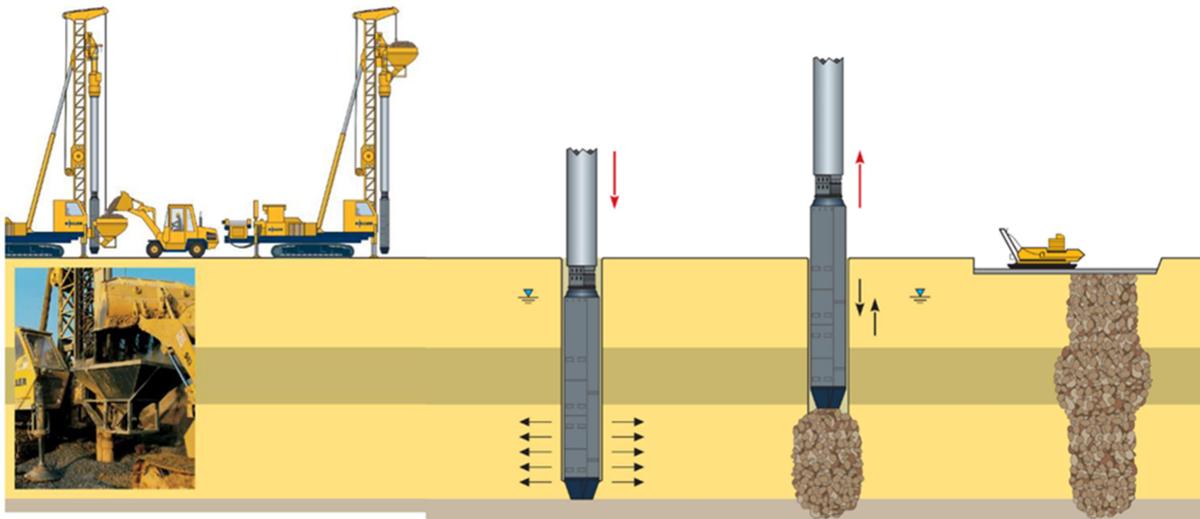
Among the geotechnical technologies that improve the load-bearing capacity of the soil substrate, the stability of slopes and embankments, including dynamic stability, as well as reducing displacements and deformations, vibro-replacement can be considered the fundamental and most reliable method. The execution of sand, sand-gravel, or gravel columns using this technology allows for the appropriate reinforcement of the soil substrate to meet the

required design parameters. This reinforcement is achieved in two ways: on one hand, a coarse-grained, non-cohesive material is introduced into the soil substrate, which is vibrationally compacted during installation, and on the other, the existing soil is spatially strengthened through lateral displacement and the aforementioned vibrations.

The vibro-replacement technique involves the formation of aggregate columns in weak soil using a deep vibrator with internal material feeding. In the first phase of column installation, the vibrator is filled with aggregate and penetrates the substrate under the influence of vibration and the pressure of the base machine (Fig. 1). Upon reaching the depth specified in the design or the required penetration resistance, an expanded gravel base is formed in the load-bearing soil. In the second phase, the gravel column shaft is constructed within the reinforced soil layers. For this purpose, coarse-grained aggregate is poured into the vibrator from above through a closed sluice.

As the vibrator is gradually lifted, the aggregate flows out from beneath the vibrator's tip with the assistance of compressed air, filling the space previously occupied by the vibrator. Subsequently, lowering the vibrator again causes the aggregate to be pushed sideways, increasing the effective diameter of the column. This reciprocating movement of the vibrator is continued along the entire length of the gravel column. During the formation of the shaft, the column diameter adjusts to the lateral deformability of the soil, ranging from approximately 0.5 m to even 0.8 m, meaning that in weaker soils, the diameter is larger, while in more resilient soils, it is smaller. Due to the shape of the vibrator, the column assumes an oval cross-section. An additional effect accompanying the formation of the gravel column shaft is the improvement of the mechanical properties of the surrounding soil. The native soil undergoes further strengthening due to compaction (in the case of granular soils) or accelerated consolidation (in the case of water-saturated cohesive soils). The required substrate stiffness, meeting the serviceability limit state (SLS) requirements, is achieved by employing an appropriately designed grid of columns with a specified diameter and length. A characteristic feature of soil reinforcement using vibro-replacement columns, which are treated as elements of spatial soil improvement, is their ability to significantly reduce settlement, particularly in weak soils. The adopted soil reinforcement method is volumetric, leading to a relative enhancement of the strength parameters of the soil between the columns. The construction of a gravel column head ensures the flexible support of the railway embankment, eliminating the risk of a punching effect. An important aspect of this technology is the ability to adjust the length of each column to actual soil conditions at a given point, thanks to the continuous measurement of the vibrator's penetration resistance in the substrate.

The equipment used in vibro-replacement technology allows for flexible delivery of various types of materials forming the column within the soil. These materials may include aggregate, a cement-gravel mixture, or semi-dry concrete. Given the lack of technological limitations, in cases where organic soil layers exceed the diameter of the column, cementation of part of the gravel column shaft should always be considered.

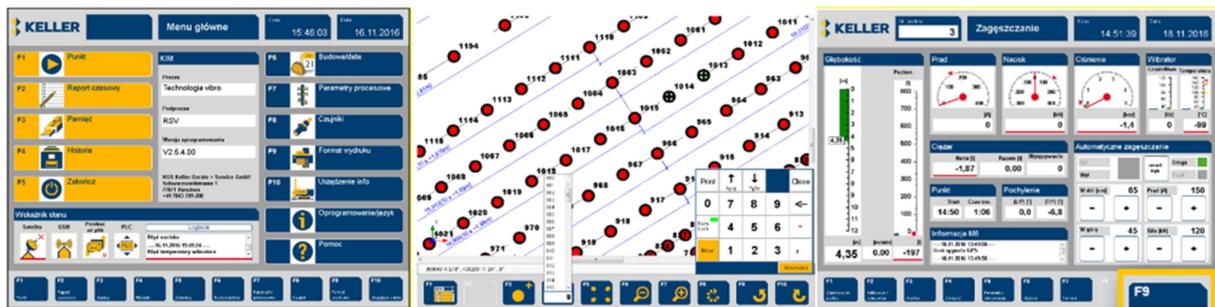


1. Diagram of gravel column installation [4]

Achieving the intended ground reinforcement parameters outlined in the design phase is not feasible without the use of appropriate equipment that ensures control and monitoring of the technological process at every stage. This equipment features advanced structural solutions as well as a quality control system and production parameter recording [2]. The equipment must provide sufficient downward force to facilitate the vibrator’s penetration through more compacted soil layers with the assistance of compressed air, enable the installation of columns of a length determined by the requirement to reach the load-bearing layer while continuously measuring the penetration resistance of the vibrator in the substrate, allow the introduction of aggregate to the required depth and the formation of an enlarged gravel base in load-bearing soil, and ensure full control over the amount of embedded aggregate and the compaction of the column shaft during its formation along its entire length (Fig. 2 to Fig. 5). Only such technical solutions allow for the utilisation of one of the fundamental characteristics of gravel columns—their self-regulation capability, meaning their ability to adapt to the lateral flexibility of the soil and the applied loads. These solutions also help minimise friction on the vibrator casing and extension tubes, thereby achieving high operational efficiency without compromising product quality.



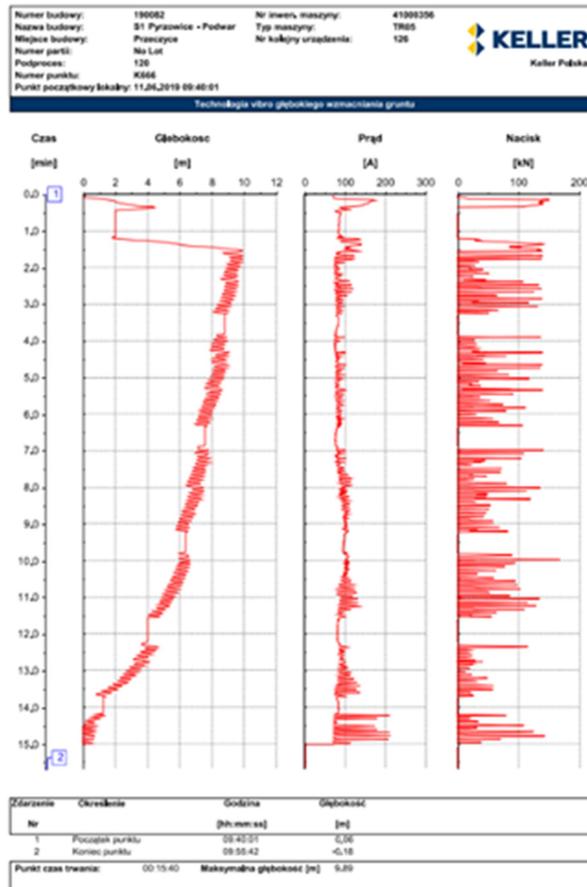
2. View of the quality control and data recording system with the production control panel in the operator’s cabin [4]



3. Quality control and data recording system [4]



4. Machine for gravel column installation [4]



5. Record of a completed column [4]

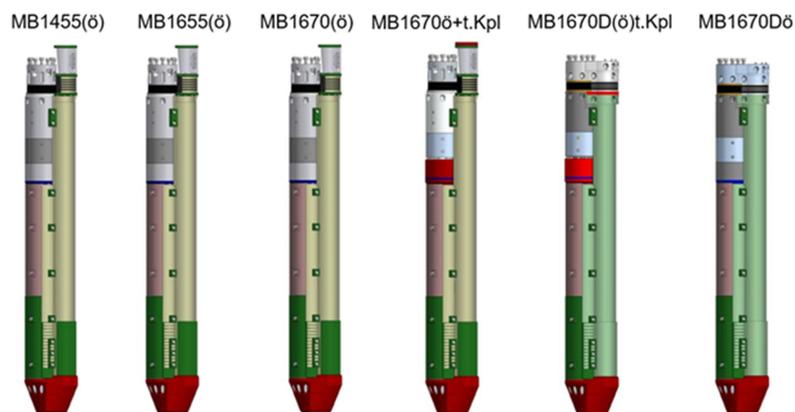
The GPS positioning system installed on the machines (Fig. 6) enables precise determination of reinforcement point locations on the working platform, replacing traditional geodetic measurements and accelerating the production process, particularly for large-scale projects.



6. Machine equipped with a GPS positioning system [4]

Effective compaction requires the use of an appropriate type of vibrator, one of the key components of the entire system (Fig. 7). Vibrators differ in power, frequency, vibration amplitude, and centrifugal force, and the selection of these parameters according to soil conditions is of fundamental importance. It should be emphasised that the vibrator, as a source of vibrations, must be mounted at the lower part of the working tool so that energy is

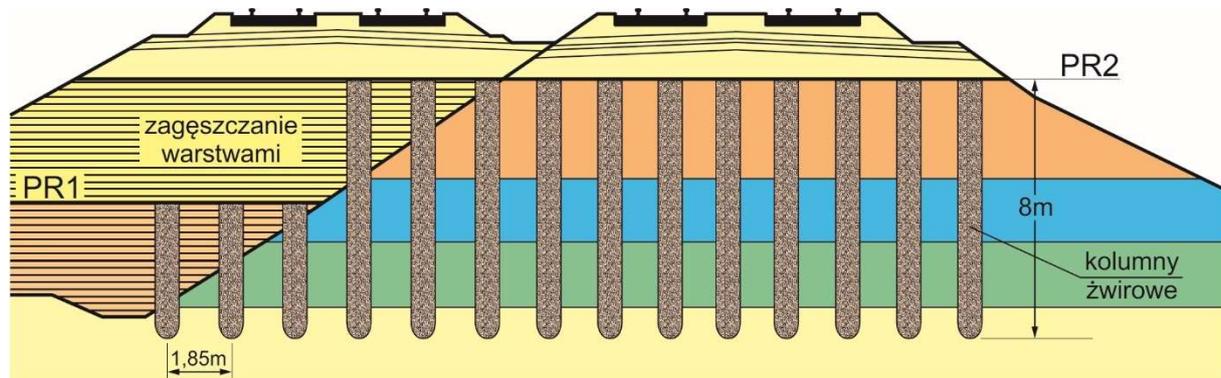
generated precisely where it is needed for compaction. This eliminates long transmission paths with significant damping losses, as is the case with top-mounted vibrators. Such solutions require a tube with a diameter corresponding to that of the column, which in turn necessitates the use of a larger carrier machine, generating the need for a more stable working platform, increased energy consumption, and often, due to the lack of pressing force, additional pre-drilling equipment, significantly increasing the implementation costs. Top-mounted vibrators have significant depth limitations, allowing for the execution of ‘columns’ only a few metres long, without the ability to control the construction process or engage the surrounding soil in cooperation, particularly in weak soils. Among other reasons, the PN-EN 14731:2005 standard does not permit the vibro-replacement method using top-mounted vibrators. Both the main machines and vibrators are designed and manufactured by KGS Keller Geräte & Service GmbH, a subsidiary of the Keller Group, whose factory is located in Renchen, Germany.



7. Types of vibrators for vibro-replacement [4]

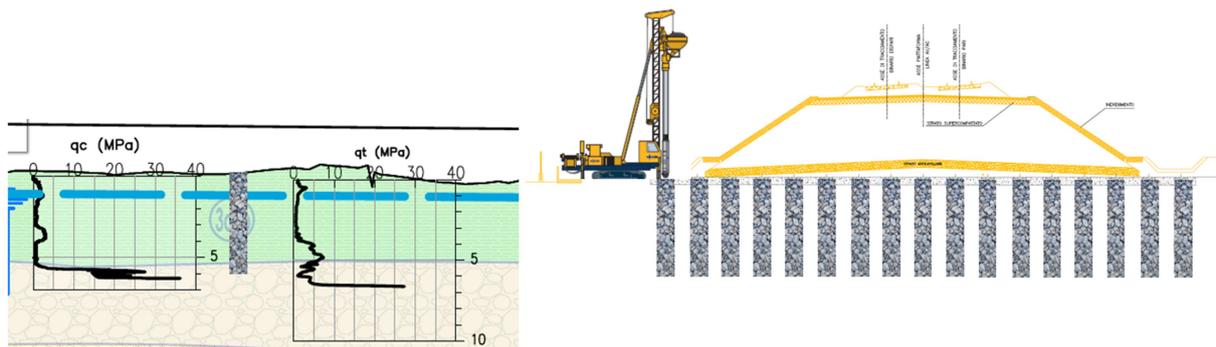
Sand, sand-gravel, and gravel columns using the vibro-replacement technology have been implemented in Poland for over 20 years across all sectors of construction. When discussing examples of vibro-replacement column applications for conventional railway lines in Poland, it is worth mentioning the soil reinforcement on line 227/249 and at Gdańsk Zaspą Towarową station, as well as on line 722 as part of the *Improvement of Railway Infrastructure Access to the Port of Gdańsk* project, which Keller completed in 2020. Based on static analyses conducted using the widely applied Priebe method, the project adopted gravel columns at nominal spacings of 1.8 m × 1.8 m (Fig. 8) and, within the transition zones, at 2.5 m × 2.5 m. The applied transverse spacing and staggered layout of the vibro-replacement columns ensure uniform reinforcement of the track bed, regardless of the geometric position of the track. To minimise settlement differences and provide a gradual change in substrate stiffness between the existing, non-reinforced soil and the reinforced section, transition zones were designed in each case. The purpose of the transition zone is to equalise settlement at the junction of the reinforced and non-reinforced areas, preventing the so-called ‘step effects.’ The project specified that the base of the vibro-replacement columns should be embedded at least 1.0 m into load-bearing soil; however, the designed column lengths are always subject to final verification on-site, based on the observed and recorded soil resistance during execution. Following the completion of works (Fig. 9), from the final acceptance (marking the beginning of the warranty period), the track settlement range should not exceed the permissible values of 4 mm per year over 30 m or 10 mm per year over 200 m, in accordance with §7 of the Id-3 instruction and the total allowable settlements specified in the construction design: $s_{dop} \leq 1.0$ cm.

The gravel columns, arranged in an orthogonal grid of 1.85×2.15 m and approximately 8 m in length, ensured compliance with the load-bearing and serviceability limit state requirements for the designed railway line.



10. Typical cross-section of soil reinforcement using vibro-replacement [4]

In 2022, Keller Foundazioni completed several sections of soil reinforcement using vibro-replacement technology for high-speed rail (Eurostar Italia), installing gravel columns beneath embankments for the new Milan–Venice railway line in Italy. Part of the route passes through the Lake Garda region, where weak lake-origin soils were reinforced as part of the project.



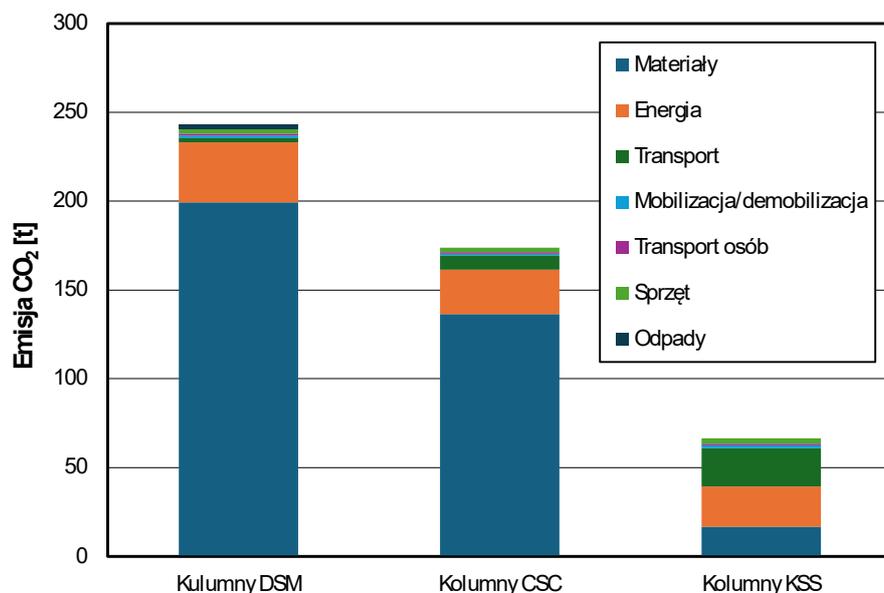
11. Example scope of soil reinforcement using vibro-replacement [4]



12. Implementation of vibro-replacement columns [4]

Due to many years of global experience in the implementation of gravel columns for soil reinforcement, numerous technical publications contain scientific articles describing the positive impact of this reinforcement on dynamic stability. Study [5] found, among other things, an increase in critical velocity ranging from several to dozens of percent in weak-bearing soils after reinforcement with gravel columns. Study [6] analysed various scenarios of a single or two trains moving at different speeds and in different directions, both on soil reinforced with gravel columns and without such reinforcement. In the reinforced scenario, a reduction of up to 50% in vertical track deformations was recorded when a single train passed at 300 km/h.

Environmental considerations are now a key aspect of construction projects. Soil reinforcement technologies that do not use concrete or cement generally result in significantly lower CO₂ emissions. This is confirmed by carbon footprint calculations carried out using a calculator developed with the participation of the European Federation of Foundation Contractors (EFFC), comparing construction projects identical in technical terms but executed using different technologies and materials [3]. Gravel column technology proves particularly advantageous in this regard, as it relies on natural materials (gravel, sand), reducing emissions by up to 80% compared to solutions using steel, concrete, and cement (such as piles and cement or reinforced concrete columns).



13. Comparison of CO₂ emission calculations for CSC, DSM, and gravel columns for reinforcement works valued at approximately PLN 500,000, calculated using the EFFC calculator

The development of High-Speed Rail is a well-justified direction for transport infrastructure advancement in our country. While we must address new technical challenges, we also benefit from the knowledge and experience gained from similar projects in other countries. In the field of geotechnical works, various solutions are available—ranging from soil reinforcement to piling—that ensure compliance with the required conditions for track beds. However, vibro-replacement technology appears to be one of the leading methods, as it is proven and virtually fail-safe due to the full control of production parameters. It has been used in High-Speed Rail projects worldwide for many years, providing a safe and environmentally friendly foundation.

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