Strengthening Methods for Subsoil under Existing Railway Lines

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Abstract
Many currently available methods for strengthening of subsoil require an interruption of railway traffic. Track and sleepers have to be removed, ballast, sub-ballast and often the embankment fill have to be excavated in order to perform the strengthening works. Such methods are complicated, time consuming and always very expensive. There is a desire to perform strengthening with a minimal impact on railway traffic without or with only marginal reduction of actual train speeds and axle loads. Practical application of such methods considerably eliminates the costs for the remedial measures and expenses due to traffic interruption. The paper provides overview of those methods that can be utilized for strengthening of subsoil under existing railways with the minimal impact on train operation. The second part of the paper presents the description of a practical case where strengthening of subsoil using inclined lime-cement column walls is suggested.

Introduction
Many railway lines in the world are 60 to 100 years old, and are not designed in accordance with requirements for modern railway traffic. Due to the future demands for faster and heavier transports, railway structures can experience problems, such as reduced stability, increase of settlements, and possibility of extensive vibrations. These issues have an adverse effect on the safety, reliability, and economy of the railway operations. Therefore, many existing railways require upgrading before the opening for new traffic conditions. Engineers are faced with the task to assess the performance of structures and if necessary to design appropriate strengthening measures.

There are many methods to improve stiffness of subsoil on the market. Contractors can offer various strengthening suggestions for all types of geotechnical conditions, track and subsoil geometries. In many cases decision about using a certain method depends on available machines and contract limits for each project. To find best solution and decide about feasible method for soil improvement of a new constructed railway line, use not to be a problem. Much more complicated is to carry out some remedial work under existing track and under train operations. There are two possibilities. Either close the train operations and remove the track and embankment and perform strengthening, or to execute subsoil stabilization without traffic interruption. It is well known that the first described option is very expensive and time consuming. An indication how the distribution of costs can look like for an actual project is obvious from the Figure 1.

![Figure 1: Distribution of cost for the countermeasure - Lime/cement columns Ledsgård, Sweden](image-url)
Presented figures show costs for strengthening work only [4]. The additional costs due to the fact that that the track could not been open for train operation under a certain period and the traffic had to be redirected are not included. One can see that the cost for installation of lime/cement columns is 16% of the total cost only. If it is compared with 56%, the cost for ground and track works it is very remarkable. It is clear that there is a great economical and traffic interest to use soil improvements methods that can be used without any, or very little, interference with existing railway track.

Overview of strengthening methods for subsoil under existing railway lines

There are number of railway, installation and geotechnical related issues to be solved before feasible soil improvement is chosen. The first one is always the cause of problem for what a strengthening has to be performed. Basically there are three types of problems. Settlements, stability and track or environmental vibrations are the main causes that can require strengthening of subsoil. In all those cases increasing of subsoil stiffness is the main objective. It is not a method of strengthening which is different for mitigation above mentioned problems, but placement and dimensions of strengthening that can be different from case to case. As regards an installation there are two possible ways. Installation can be performed from the track or from sides of railway embankment. Both methods have advantages and disadvantages.

Installation of strengthening from the track is usually done by equipment and tools mounted on railway vehicles. Results are commonly good since strengthening is placed directly under the track. If the traffic should not be restrained, installation has to been done between sleepers. Space about 40 cm between sleepers often requires a special tool. There can be even restriction about the available time for installation of strengthening due to demanded train traffic. Further issues which have to be considered are the cables placed in formation and embankment like security space between installation machines and contact wire, poles and catenary suspensions. In many cases it is not possible to carry out installation with absence of voltage in the wires. Some methods especially those ones using bindings can pollute ballast during the installation. Again special tools have to be utilised to assure clean ballast otherwise the strengthening method applied from the track is not acceptable.

Installation of strengthening from sides of railway embankment is easier to perform since there is less contact with existing track and catenaries. But not in all cases there is a sufficient space on sides of the railway, since there can be not removable objects like houses etc. close to the track. In some projects working platforms has to be constructed for heavy machines used for soil improvement installation.

Risk dealing with railway operations during the installation work has to be avoided. Effects of strengthening methods and installations on track and environment are well known. All methods used for soil improvement under the rail traffic have impact on track geometry during the installation. Expected deterioration and limits for track geometry are important to assess together with allowable train speed and axle loads during the construction. A plan for control and measurements for the time of the contract work have to be prepared before the beginning of the work. Often even a plan for track levelling is recommended especially if the track deterioration can be predicted. In some cases often a more advanced monitoring is inevitable. An automatic stop of a train can be required to avoid a derailment in case of the sudden deterioration of the track due to strengthening is feared. Soil strength directly after the installation has to be considered. There are methods there soil strength can considerably decrease for certain time after the installation, followed by increase of strength with time. This phenomenon can have an impact on train transport and access of heavy and speedy trains. Sometimes it is not possible to carry out installation in a stretch and division to certain stages is necessary. Again the impact on the track has to be considered and shifts of installation machines can be required.
**Geotechnical issues** and their impact on safety and limits for operation are very important. Parameters of soil before, during and after strengthening must be assessed with consideration of time related connections. Of course the design of the soil improvement has to assess degree of safety for the improved structure and for all stages of strengthening work. Especially stability and conditions for possible failures of railway have to be evaluated. Deformations in form of settlements, horizontal movements and twist should be estimated. This helps with planning of machines and number of track levelling during and immediately after the subsoil improvement.

<table>
<thead>
<tr>
<th>Scheme</th>
<th>Method</th>
<th>Principle</th>
<th>Can be performed without affecting traffic</th>
<th>Applicable soils</th>
<th>Increase of Stability</th>
<th>Reduce of Settlements</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image1" alt="Deep Mixing, beside railway embankment" /></td>
<td>a) Deep Mixing, beside railway embankment</td>
<td>Mixes in-situ soils with cementitious materials to form a vertical stiff inclusion in the ground</td>
<td>Yes</td>
<td>Wet method: most soft soil types; Dry method: soft fine-grained soils</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td><img src="image2" alt="Deep Mixing, installed inclined under embankment" /></td>
<td>a) Deep Mixing, installed inclined under embankment</td>
<td>Mixes in-situ soils with cementitious materials to form an inclined stiff inclusion in the ground</td>
<td>Yes</td>
<td>Wet method: most soft soil types; Dry method: soft fine-grained soils</td>
<td>X X</td>
<td></td>
</tr>
<tr>
<td><img src="image3" alt="Deep Mixing, installed through the track and embankment" /></td>
<td>a) Deep Mixing, installed through the track and embankment</td>
<td>Mixes in-situ soils with cementitious materials to form a vertical stiff inclusion in the ground</td>
<td>No (Yes, if performed during periods with no traffic)</td>
<td>Wet method: most soft soil types; Dry method: soft fine-grained soils</td>
<td>X X</td>
<td></td>
</tr>
<tr>
<td><img src="image4" alt="Jet grouting" /></td>
<td>b) Jet grouting</td>
<td>Erodes soil in situ and mixes with cementitious materials to form stiff inclusion in the ground</td>
<td>Yes (unless installed beneath embankment)</td>
<td>Most soil types</td>
<td>X X</td>
<td></td>
</tr>
<tr>
<td><img src="image5" alt="Stabilizing berms, alone or in combination with anchored walls" /></td>
<td>c) Stabilizing berms, alone or in combination with anchored walls</td>
<td>Compacted material constructed adjacent to embankment. Driven walls provide resistance against horizontal movements.</td>
<td>Yes</td>
<td>Clay</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td><img src="image6" alt="Compaction grouting" /></td>
<td>d) Compaction grouting</td>
<td>Low slump grout is pumped into the ground, which displace and densify the soil or fill voids in rock</td>
<td>Yes</td>
<td>Granular soil</td>
<td>X X</td>
<td></td>
</tr>
<tr>
<td><img src="image7" alt="Concrete slab on piles" /></td>
<td>e) Concrete slab on piles</td>
<td>Installation of piles on both sides of railway, precasted slabs fixed on piles in short stages with traffic interruption</td>
<td>No(Yes, if performed during periods with no traffic)</td>
<td>All soil types</td>
<td>X X</td>
<td></td>
</tr>
<tr>
<td><img src="image8" alt="Soil nailing" /></td>
<td>f) Soil nailing</td>
<td>Soil nails installation between sleepers</td>
<td>No(Yes, if performed during periods with no traffic)</td>
<td>All soil types</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td><img src="image9" alt="Vibro compaction" /></td>
<td>g) Vibro compaction</td>
<td>Compaction of soil, transfer of loads to more competent strata through friction or end-bearing</td>
<td>No (Yes, if performed during periods with no traffic)</td>
<td>Granular soils (Vibro compaction) All soil types (Other methods)</td>
<td>X X</td>
<td></td>
</tr>
</tbody>
</table>

Table 1: Overview of existing strengthening methods
Short description and principals for soil strengthening methods

Table 1. gives the principal overview of the main known existing strengthening methods that can be relevant for strengthening of subsoil without total stopping of railway operations [3], [4], [9]. There can be found more methods and variations on the market, since contractors continuously develop or improve methodology suitable for their machines, local geotechnical conditions and railway related needs.

a) Deep Mixing Method

The deep mixing method is a technology that mixes in-situ soils with cementitious materials to form a vertical stiff inclusion in the ground [2], [5], [6], [8], [10], [15]. A mixing tool is rotated down to the design depth and once the design depth is reached, the direction of rotation of the mixing tool is reversed and the tool is withdrawn at a constant rate. During advancement and/or withdrawal of the mixing tool, agents such as quicklime, slaked lime, cement, and fly ash are forced into the ground. The agents, widely referred to as binders, may be introduced in the form of either a dry powder or wet slurry. The wet methods of deep mixing are usually designed to provide higher unconfined compressive strengths values than the dry method. The MDM (Modified Dry Mixing) switches seamless from wet to dry during each individual installation. This technique facilitates penetration of stiff soils, fluidises low plastic clays as well as ensures the complete hydration of the added binder. The deep mixing method produces columns in the ground that can be installed singularly, or in rows, grids, or blocks. The design spacing, diameter and length of columns depends on such factors as the allowable total and differential settlements, and the required capacity to prevent stability failures. Single dry-mixed columns are typically spaced at 1.0 to 1.6 m, center-to-center, and diameters range from 0.4 to 1.0 m. Single wet-mixed columns are typically installed with diameters ranging from 0.9 to 2.4 m. The maximum depths of treatment for the dry and wet methods of deep mixing are about 35 m and 40 m, respectively.

Experience with the installation of deep mixed columns through existing railway embankments from field test performed in Germany and United Kingdom have been published [11], [13], [14].

b) Jet Grouting

The jet grouting technology is very similar to the deep mixing technology except that very high-pressure fluids are used in the jet grouting technology to erode subsurface soil particles and mix them with cement. The jet grouting uses hydraulic energy in order to erode the soil, and to mix/replace the eroded soil with an engineered grout of water and cement to form a solidified in situ element. Jet grouted elements can be installed in a variety of subsurface geometries. Columns with diameters of 0.6 to 2 m are typical. Jet grouted columns can be formed vertically, horizontally, or at an angle. There are three traditional jet grouting techniques. Single-fluid jet grouting uses high pressure (400 to 500 bar) grout only; double fluid-jet grouting uses high pressure grout sheathed in compressed air; and triple-fluid jet grouting uses high pressure water sheathed in air followed by a second jet of high pressure grout. The equipment to perform jet grouting remains specialized but many contractors are available to carry out this technology. Drills range from relatively small electrically powered units up to the large crane supported systems, and some drills have the ability to create a wide variety of jet grouted geometries. Theoretically, treatment depth is unlimited, but jet grouting has rarely been performed in depths deeper than 50 m.

c) Anchored walls Combined with Stabilising Berms

Stabilising berms are often constructed adjacent to existing railway embankments to increase the resistance of the embankment to prevent stability failures. Stabilising berms consist of a few meters of compacted material and can be about 1 to 2 m high. The use of loading berms is an effective way of increasing stability conditions, and the costs are often competitive compared to other methods. However a main disadvantage of the method is that it does not reduce settlements or vibration effects. In fact, the settlements of the railway embankment can increase
when loading berms are used. This negative effect can be reduced by combining the loading berms with walls installed along the railway embankment. Figure 2 shows an example of the sheet pile wall used for stabilising of existing embankment [7]. Walls can be created for example as pile walls using concrete, steel or wooden piles. Sheet piles had been used as well like diagphram walls. Material used for supporting wall depends on geotechnical conditions, load and geometrical situation of the particular project.

Figure 2: Exemple of anchored sheet pile walls in combination with stabilizing berms: (a) principle of technology, and (b) photo of the wall at a site in Vitmossen, Sweden.

The anchored wall system reduces or eliminates shear deformations. By extending the walls so that the slopes can be made less steep, the creep of steep slopes of embankments is mitigated. Furthermore, the use of the anchored wall system allows often required widening of existing railways. Stabilising berms are constructed using compacted fill. If walls are installed on both sides of the railway embankment, anchors can be installed to connect the walls on opposing sides of the embankment. The anchors are post-tensioned to reduce horizontal movements in the walls. Stabilising berms can only be constructed above soil with adequate bearing capacity. Prior to constructing stabilising berms, the predicted total and differential settlements should be evaluated. It could be problematic to install driven elements, like for example sheet piles, through subsurface soils containing cobbles or boulders. In this case drilled or predrilled structures are more feasible.
d) Compaction Grouting

The compaction grouting is a technology that injects a low slump grout into the ground to form a stiff, homogenous mass in the subsoil. The grout does not enter soil pores but remains in a stiff mass that gives controlled displacement in order to compact granular soils. The compaction grouting is commonly used to increase the density of soils. The grouted mass also add the strength in the vertical axis, since the grout compressive strength is much higher than that of the native soil. There are a number of applications of compaction grouting including remediation of embankment settlements, soil densification for site improvement, filling of voids in rock formations and liquefaction mitigation. Compaction grouting is performed by injecting a very stiff grout through a casing at a high pump pressure; the casing is withdrawn incrementally and a column of interconnected grout bulbs is created. The grout is performed through the use of vertical or inclined grout pipes.

e) Concrete Slab on Piles

Advantage of this method is that piles and longitudinal beams are installed in advance on both sides of the existing railway without any disturbance of traffic. The pre-cast slabs are placed on piles after replacement of track in short traffic brakes usually during nights and than the track is reopen for the train operations again [16]. In this way a continuous long distance of track can be mitigated with a minimal impact on traffic. Principe of Concrete Slab on Piles is shown in the Figure 3.

f) Soil Nailing

Soil nails can be driven from the track to the underground from the space between sleepers. En example of trial soil nailing is shown in the Figure 4. Soil nails can be installed through the ballast to all designed inclination and positions [12]. The technique is very effective and simple with minimal disturbance of the tack level. Tamping of ballast after nails installation is usually required. This method is relatively cheap with high production in comparison to the other described methods. Further development and more studies of effectiveness of this method are desirable.
g) **Vibro Compaction, Vibro Replacement (Stone/Gravel Columns), Grouted Stone and Vibro Concrete Columns**

**Vibro Compaction** is a suitable method for densification of cohesion less granular soils like sands, gravel or crushed rocks. Principle of this method is the reduction of pores content and increase of stiffness by vibration. Usually a vibrator penetrates to designed depth and than this is withdrawn in steps until required compaction is achieved. During compaction additional material has to be added since volume decreases. This method has to be applied very carefully on operated railways because the settlements of the track can be up to 15 % of the treated volume. Additional ballast, sub-ballast like more friction material is recommended to be available for immediate levelling of the track.

**Vibro Replacement** can be used for all types of soils. This method is combination of vibration and replacement of cohesive soils with granular material. The vibrator penetrates to a design depth and cavities are filled with course material free of clay or silt. In this way non-compactable soils are improved with well graded load bearing columns. Gravel, crushed stones or sand can be used as a filling of columns. In case air pressure is used one speaks about “dry bottom feed technique” and “wet bottom feed technique” is called installation if pressurised water is used. The dry bottom feed technique is more suitable for railways due to the less risk for unacceptable settlements and change of consistency of cohesive soils under the track. The risk for excessive settlements during the installation is lower than for Vibro Compaction but certain care has to be taken and even here additional ballast, sub-ballast like more friction material have to be available in case levelling of the track is required. In soft soils there is often a steel casing pipe vibrated to the soil. This method is called displacement installation of stone/gravel columns. When pipe is withdrawn filling material is vibrated in, to create the stone or sand columns. Even geotextile tube can be used to stabilize and improve performance of the columns. In this case the method is called “Geotextile Coated Columns (GCC)”.

![Figure 4: An example of soil nailing](Image) – Courtesy to University of Birmingham UK
Grouted Stone Columns (GSC)

Lateral support in very soft clay or peat is usually not sufficient for adequate stability and bearing capacity of columns. In the description of the Vibro Replacement method there is mention application of geotextile to achieve a better lateral support. Another way to improve stone columns is to use cement grout suspension during the installation process. Cement grout suspension forms together with course material a stiff body of the column. Of course such columns show much higher bearing capacity than previous described methods. Even possible impact on the track during installation is lower but the time for hardening of the cement grout has to be considered together with the next train operations.

Vibro Concrete Columns (VCC)

Rigid piles like deep foundation elements of high bearing capacity can be created by using the Vibro Concrete method. In this case the concrete is directly pumped to the tip of bottom feed depth vibrator. Those columns are usually considered as end bearings columns since foundation base penetrates to bearable layers. Those columns are suitable for very soft soils when higher loads need to be transferred to stiffer and bearable strata and reduce settlements to minimum. Under existing railways the head columns should be enlarged to obtain better support for sleepers. To avoid concentration of stresses in ballast the top of column head should be placed deeper in the formation. It is a common design that is applied for driven or pre-cast concrete piles under railway embankments.

Strengthening of subsoil with inclined lime-cement column walls – case study

Author of this paper participates in railway related European Union project INNOTRACK that started in the autumn 2006. Measurements and assessment of status of existing railway lines, like development of substructure strengthening methods which can be applied without interruption of railway operations are the main objectives of the research in civil engineering part of the INNOTRACK project. Since there is an urgent need for upgrading of existing railway lines and at the same time there is no possibility to close lines for operations to improve subsoil under the track, the needs to test and develop new methods for the subsoil strengthening are obvious. Questions dealing with impact of the strengthening on existing railway under the installation of subsoil improvement are further issues of the INNOTRACK project.

The deep mixing method has been used since 1970-ties in Japan and Nordic to stabilize subsoil under embankments. The deep mixing procedures produce improved ground that has greater strength, lower ductility, and lower compressibility than the original ground. The degree of improvement depends on the amount and type of stabilizer, installation process, characteristics of the original ground, and the curing time. The deep mixing method is a technology that mixes in-situ soils with cementitious materials to form a vertical stiff inclusion in the ground. A mixing tool is rotated down to the design depth, and once the design depth is reached, the direction of rotation of the mixing tool is reversed and the tool is withdrawn at a constant rate. During advancement and/or withdrawal of the mixing tool, agents such as quicklime, slaked lime, cement, and fly ash are forced into the ground. The deep mixing method produces columns in the ground that can be installed singularly, or in rows (walls), grids, or blocks. When installed vertically the soft soil beneath the railway is stabilized. Vertical strengthening is normally used for new constructed railways and there is an extensive experience with the application of deep mixed columns to support new railway embankments.

However, there is little experience with the installation of deep mixed columns through existing railway embankments [11], [13], [14]. It is well known, that there is a good experience in Scandinavia with installation of vertical columns beside the railway embankment to increase the stability of subsoil. On the other hand there is a limited experience with the installation of inclined overlapping deep mixed columns in walls under the existing railway embankment. The
objective of the presented research performed by Banverket is to develop and demonstrate a new innovative solution of the subsoil improvement. Suggested test site is situated on the Southern Main Railway Line, railway between Norrköping and Linköping, at a place named Torp. An insufficient stability of the embankment has to be increased to allow an upgrading this railway line to axle load 25 t. (22.5 t axle load at the present time). Strengthening of the sub-soil with inclined lime cement columns walls is suggested and a design was finished in the autumn 2006. Figure 5 demonstrates a layout of soil improvement with inclined lime cement column walls.

Figure 5: Design of strengthening of subsoil using inclined lime cement column walls

A full scale IN-SITU test is planed to be performed in 2008. The investigations will comprise of assessment of subsoil properties below the existing embankment. The long-term behaviour of natural and improved soil like related modelling dealing with new methodology of subsoil strengthening is going to be the part of suggested studies. The full scale test will prove an efficiency of strengthening of subsoil using inclined lime cement columns walls situated under the railway and impact on the track geometry during the installation. The suggested methodology is designed with consideration of a minimum influence on the traffic (track availability for railway operations) and the environment of this existing railway. The planed measurements will concentrate on the first place on the impact of installation on the existing railway track. There is not allowed to decrease the contemporary train speed of 180 km/hour. Regular controls have to be done during the whole soil strengthening work and special checks after passage of each particular train will be necessary. The limits for track geometry deterioration will be assessed like the values there some track leveling have to be done before the operation will be allowed, in case of some track movements. Further measurements are going to control displacements of the track and the surroundings in vertical and horizontal direction. Inclinometers, settlement measurement devices like pore pressure and ground water indicators are planned to be installed in order to get comprehensive information about behavior of the embankment, subsoil and the lime cement strengthening. Suggested plan of measurements and position of instrumentation is shown in the Figure 6. An important part of the project is a control of the quality of soil improvement. The strength of soil after dry mixing in walls, geometry and homogeneity are the main objectives of in-situ tests sampling and laboratory testing during and after installation of the strengthening. Complementary geophysical investigations like a seismic tomography are suggested to carry out with an aim to assess the geometrical form and homogeneity of individual lime cement inclined walls. The full scale IN-SITU tests are an introduction part of the total soil improvement of about 1200 m of railway. After finishing and evaluation of the full scale test the design for the main project is going to be adjusted and the main strengthening is going to be performed.
Strengthening of the subsoil under existing tracks and keeping train operations at the same time is a very difficult task. Combination of two objectives like achievement of perfect stabilization of soil and minimize an impact on track geometry is very difficult to fulfill at the same time. In many cases a considerable decrease of the train speed is necessary to assure a safety of the train operations. There is an experience that a low speed at the section where the strengthening is carried out for a limited time, is more acceptable, than a complete long term closing of the entire railway line. Since the work is always done very close to the operated track, monitoring of all deformations of the track and at the vicinity is necessary during the time of the strengthening work. Usually a monitoring plan is prepared where limit values have to be assessed. A trespass of those values results in to a track levelling or at a limit case to a total traffic stop up to the time problem is mitigated and the track can be reopened again for the allowed speed and axle loads.

The strengthening methods described in this article are according to the author knowledge the main ones recently actual to mitigate settlements, stability or vibration problems related to railways. It is possible that there are more other methods or their variations than those ones described in this paper. The soil stabilization depends very much on machines and tools developed for this work. In many cases contractors dealing with foundation works use to developed their own methods that are suitable to certain area (country) geotechnical conditions and tools that are adjusted for their own machineries. Choosing the best method is always a process to find the best solution considering a number of technical, economical and railway related issues. The problem has to be mitigated with most effective technical and economical method, within a very short time and with the minimal impact on the operated track.

Acknowledgements

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