Integrated Project (IP)
Project No. TIP5-CT-2006-031415

Thematic Priority 6:
Sustainable Development,
Global Change and Ecosystems

Guideline for subgrade reinforcement with columns

Part 1 Vertical columns

Part 2 Inclined columns

INNOTRACK GUIDELINE

Deliverable D2.2.8

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1. Subgrade strengthening with lime/cement or soil/cement columns

Executive summary

Two methods for subgrade improvement have been tested. The results are presented in a special INNOTRACK report "D2.2.5 – Subgarde reinforcement with columns – Part 1 Vertical columns and Part 2 Inclined columns".

Vertical columns – LCPC (France)

In-situ load tests were carried out with soil-cement columns on a test site of Northern France with four partners; KELLER FOUNDATIONS, LCPC, SNCF and SOLETANCHE BACHY. Two types of tests have been carried out:

- standard load tests have been performed on columns built in a zone located outside but close to an existing railway, near an water retaining basin. During such tests, the columns are subjected to a vertical load, increased progressively until failure (or a state near failure) ; the test results is the curve of the column head vertical displacement as the applied load increases, and the distribution of the normal force in depth along the column;
- besides, columns were built under the platform of an existing sidetrack and the vertical displacements of the column head and of the ballast as well as the distribution of the load along the column have been measured under the load brought by a train axle.

The soil-cement columns have been built by two distinct companies (KELLER FOUNDATIONS and SOLETANCHE-BACHY) on an SNCF (Société des Chemins de fer français, French Railway administration) site, and monitored by LCPC. The main differences between the columns are their

diameters (400 and 600 mm) and the tools used to achieve the soil mixing.

After the experiments, some of the columns were dug out to know their actual geometry, the quality of the soil mixing and to check whether or not the ballast has been polluted by the grout. Results appeared to be satisfactory. This report presents a synthesis on the field experiments; it also includes results of finite element simulations carried out to discuss the influence of various parameters.

Inclined columns – Banverket (Sweden)

Full scale in-situ test has been carried out using lime cement columns installed like inclined walls (panels) under existing railway embankment and without any restriction on current railway operations. The main objectives of this test were the following:

- verification of possibility to install columns in inclined way using machines and tools that are normally designed for vertical installations
- investigate impact of installation on operated track
- evaluate and control a quality of strengthening

The following conclusions can be drawn from the tests:

- The performed test installation of inclined columns panels has proved that this method of soil improvement is a possible alternative for increasing the stability of an existing railway embankment on originally soft subgrade.
- Installation of subgrade strengthening can be performed under operated railway embankment.
- There is always need to take safety precautions and consider restriction for train speed or axle loads at the time of strengthening work

1.1. 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 subgrade improvement before the opening for new traffic conditions.

Engineers have to assess the performance of structures and if necessary to design appropriate strengthening measures. Many methods are available on the market, 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. Finding a good solution for soil improvement is generally not a problem for a new line. It is more complicated to carry out remedial works under an existing track in service. There are two possibilities: either close train operations, remove the track and embankment and perform strengthening, or execute subsoil stabilization without traffic interruption.

Many railway, installation and geotechnical related issues must be solved before a soil improvement solution is chosen. The first one is the cause of problem for which strengthening is needed. Basically there are three types of problems: settlements, stability and vibrations (of the track or in the environment). In all cases increasing subsoil stiffness is the main objective. The strengthening method itself is the same, but placement and dimensions of strengthening that can be different from case to case. Installation can be performed from the track or from sides of railway embankment. Both methods have advantages and disadvantages.

In the frame of INNOTRACK project two methods for subgrade improvement have been tested. The results are presented in the report “D2.2.5 – Subgarde reinforcement with columns – Part 1 Vertical columns and Part 2 Inclined columns”. In the appendix to this report a comprehensive bibliographic study on deep mixing methods is included. There is a state of the art about development and practical application of deep soil mixing methodology.

1.2. Railway application of deep mixing for subgrade strengthening

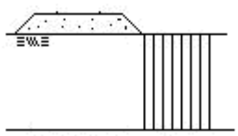
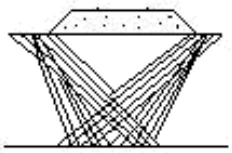
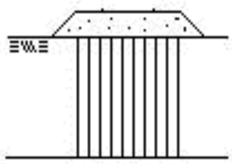
1.2.1. Methodology of strengthening installation

No	Installation requirements	Remarks
1	**Installation of strengthening from the railway track** is usually done by equipment and tools mounted on railway vehicles. Results are good since strengthening is placed directly under the track. If the traffic should not be restrained, installation has to been done between sleepers, in a space of about 40 cm, which requires special tools. There can be restriction regarding 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 the 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.	***From the railway track***
2	**Installation of strengthening from sides of railway embankment** is easier to perform since there is less contact with existing track and catenaries. But in some cases there is not sufficient space on sides of the railway, e.g. because of buildings close to the track. In some projects working platforms have to be constructed for heavy machines used for soil improvement installation.	***From sides of railway track***

1.2.2. Safety precaution and geotechnical issues

1	**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 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 must be prepared before the beginning of the work. Often even a plan for track levelling is recommended especially if track deterioration can be predicted. In some cases a more advanced monitoring is required. An automatic stop of a train can be required to avoid a derailment if a sudden deterioration of the track due to strengthening is feared. Soil strength directly after the installation has to be considered. In some cases 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.	***Safety***
2	**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. Of course the design of the soil improvement has to assess the degree of safety for the improved structure and for all stages of strengthening work. Especially stability and possible failures of railway have to be evaluated. 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.	***Geotechnics***

1.3. Overview of deep mixing technology applications in railway related projects

Scheme	Method	Principle	Can be performed without affecting traffic	Applicable soils	Increase of stability	Reduction of settlements
	a) Deep Mixing, beside railway embankment	Mixes in-situ soils with cementitious materials to form a vertical stiff inclusion in the ground	Yes	Wet method: most soft soil types; Dry method: soft fine-grained soils	X	
	a) Deep Mixing, installed inclined under embankment	Mixes in-situ soils with cementitious materials to form an inclined stiff inclusion in the ground	Yes	Wet method: most soft soil types Dry method: soft fine-grained soils	X	X
	a) Deep Mixing, installed through the track and embankment	Mixes in-situ soils with cementitious materials to form a vertical stiff inclusion in the ground	No (Yes, if performed during periods with no traffic)	Wet method: most soft soil types Dry method: soft fine-grained soils	X	X

2. Vertical columns

2.1. Introduction

The experiments carried out on vertical columns in France within the Innotrack project aimed at showing the feasibility of the technique: the knowledge obtained is limited, and the following guidelines remain to be improved and validated.

Nevertheless, a state of the art of Deep Mixing Method for railway engineering is available in D.2.2.5 (INNOTRACK, D2.2.5, 2009).

In addition, European Standard NF EN 14679 and Eurosoilstab (2000) can be consulted for further information.

Installation of vertical soil-cement columns using the wet deep-mixing method under an existing track is carried out from the track itself, which requires that traffic interruption is possible for several hours (at night for instance): this is the main disadvantage of the technique. It also requires a careful planning of works in order to ensure safety of workers and passing trains.

The main advantage of the technique is that train operation is not stopped, and that, since low grout pressures are used, heave of the track is easy to control and remains limited.

A comprehensive preparation is needed that must take into account the following items:

- Geotechnical investigation
- Test installation of soil cement columns
- Design requirements
- Choice of binder
- Installation procedure
- Monitoring and control system
- Quality control
- Risk assessment

2.2. Technical requirements for subgrade reinforcement with vertical columns

No	Requirements to be met	Remarks
1	**Geotechnical condition and investigations, test installation of lime cement columns** Field and laboratory investigations shall provide information regarding: - the sequence of soil layers and their properties; - groundwater conditions; - the presence of organic soil or sulphides and pH; - the composition, thickness, firmness of the surface stratum and any tree roots, fill, etc; - the presence of fixed obstacles to column placing (e.g. buried pipes, cables and overhead lines); -the properties of soil after the binder has been mixed in. Mixing trials are performed for characteristic soil strata.	***Basic input information***
2	**Test installation of soil cement columns**  It is recommended to test the construction procedure in a side area (and if possible to perform load tests to assess the column properties, such as the test shown on the above picture, carried out within the INNOTRACK project in the North of France).	***Field analysis of actual column performance***

No	Requirements to be met	Remarks
	The treated soil is investigated following the same standards as described above. The dispersion of in-situ strength is investigated. This investigation can be associated with laboratory tests on core samples, wet grab samples and block samples from exposed or extracted columns.	
3	**Design requirements : service life and ultimate limit states** The design of stabilised ground must satisfy ultimate and serviceability limit states. The service life is stated in construction specifications. Service Life State calculations are carried out using characteristic values. Settlement calculations should be based on the assumption that at every level the same vertical deformation occurs in columns and in the unstabilised soil. Design should check that the total and differential settlements along and across the track are acceptable in all zones including transition zones between strengthened and non-strengthened areas. The SLS must include consideration of long-term creep movements. Deep stabilisation should be combined with preloading including a temporary surcharge, designed so that parts of it can be removed at the end of the preloading period. This will reduce or eliminate future creep settlements. The Ultimate Limit States mechanisms to be considered in the design of stabilised soil include failure of the columns and overall failure through the columns and the untreated ground. The design of the stabilised ground must be such that there is a low probability of collapse of the supported structure. The choice of characteristic material values should consider the durability of the deep stabilisation.	***Technical design considering all stages of strengthening***

No	Requirements to be met	Remarks
4	**Choice of binder** The choice of binder is a critical aspect of deep mixing. Testing of binders with the soil to be treated is an essential requirement on any deep mixing project. Standard laboratory tests provide information on the binder type and dosage appropriate for the actual construction. Tests should include each representative soil layer. Preliminary design is based on the laboratory test results, database and information about similar experience. Before the actual construction, deep mixed test columns are constructed on which field trials are carried out to confirm that the dosage, type of binder and mixing energy yield the required strength and uniformity. In case field trials fail to satisfy the requirements given in the design, the functional and process design have to be reconsidered. When mixing the binder with soil the chemical reactions start immediately. When cement is used a stabilising gel between the soil granules is created due to pozzolanic reactions. A very homogeneous mixing is required since cement does not diffuse. The geo-mechanical properties of the stabilised material largely depend on the type of binder. In general, the strength and brittleness of the stabilised soil increase with increasing amount of cement.	
5	**Installation procedure** As shown by the following figure, traffic schedule shall take into account periods (e.g. hours at night) when work on the track can be performed safely.	***Traffic restrictions*** ***Construction site*** ***Special tool and machinery***

No	Requirements to be met	Remarks
	 In the case of the experiment carried out within Innotrack, preliminary boreholes were needed before the installation machine actually performed the deep-mixing (in order to cross the ballast and railway structure layers). A carrier was used to feed it with binder. A supply station was nearby. The installation procedure shall make it possible to build the columns without significant heave of the track, thanks to low grout pressures, that also ensure that ballast pollution is avoided. Plastic leafs around the borehole should also reduce potential ballast pollution. Specific tools (such as the tools of Keller and Solétanche Bachy shown on the following pictures) are needed to cross the railway structure and start column construction at the depth of the subgrade layer to be strengthened.  	

No	Requirements to be met	Remarks
6	**Monitoring and control system** The mixing tool is inserted (bored or pushed) vertically into the soil down to prescribed depth. During the injection of slurry, continuous monitoring shall be carried out automatically for the output of slurry, input pressure at machine, output pressure, lifting speed, rate of rotation. The amount of slurry overflowing at the top of the column shall be measured during installation until the slurry flow is cut off. Starting before and up to 48 hours after installation, surface heave shall be monitored (accuracy 1mm). One point per 200 m2 will be sufficient. The water to cement weight ratio shall be documented (typically in the range 0.5 to 2.0). A careful follow-up (e.g. settlements, pore pressures) during the construction stage is essential for verifying the behaviour. The deep stabilisation method shall be used together with active design (observational method). Monitoring after construction shall also be undertaken to follow the evolution of settlement and pore pressure.	
7	**Quality control** Field tests shall be performed on trial columns to verify their homogeneity and quality, e.g. Standard Column Penetration Tests or Reversed Column Penetration Test. Tests on laboratory mixed samples tend to provide somewhat higher values of shear strength. Lab tests can also be performed with core samples taken from columns built in field, to check their homogeneity and mechanical properties (see picture)	***measurements after installation of strengthening***

No	Requirements to be met	Remarks
		
8	**Risk assessment** It is essential that the appropriate measures are taken to mitigate the risk to the safety and health of personnel. The risks can be listed and rated in a risk assessment for the site works.	

3. Inclined columns

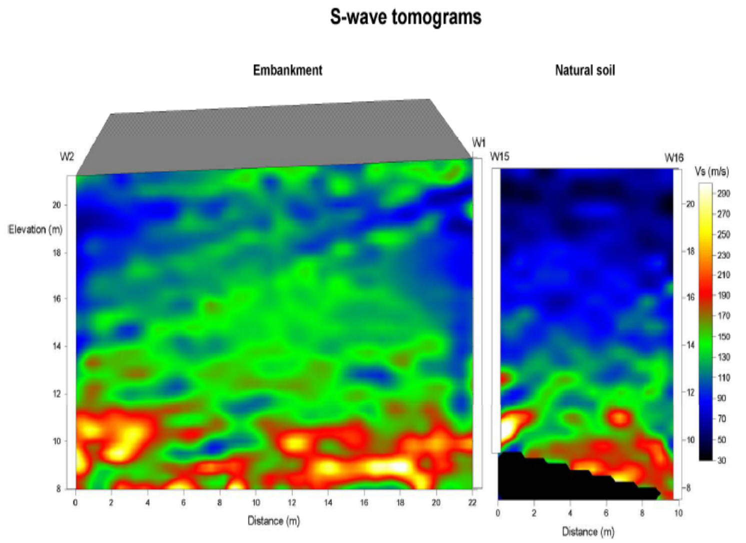
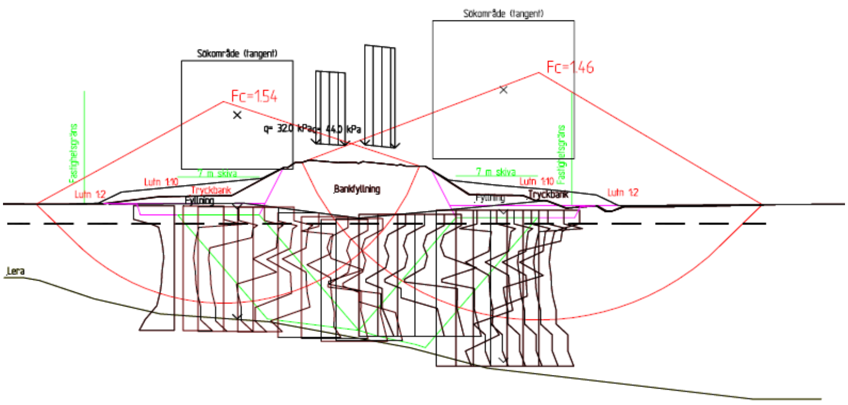
3.1. Introduction

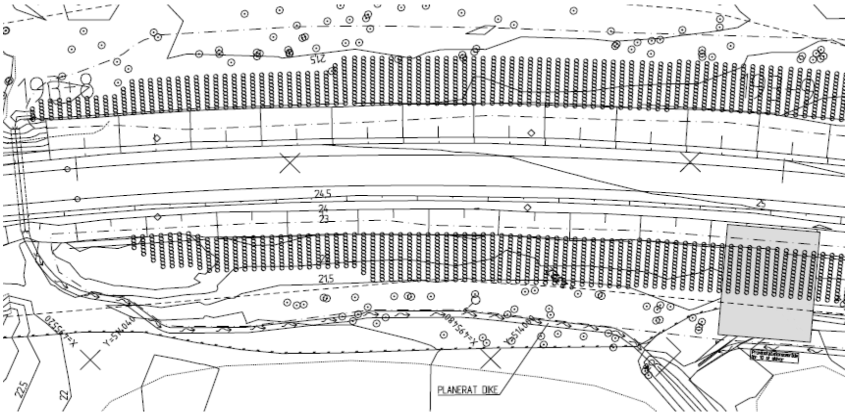
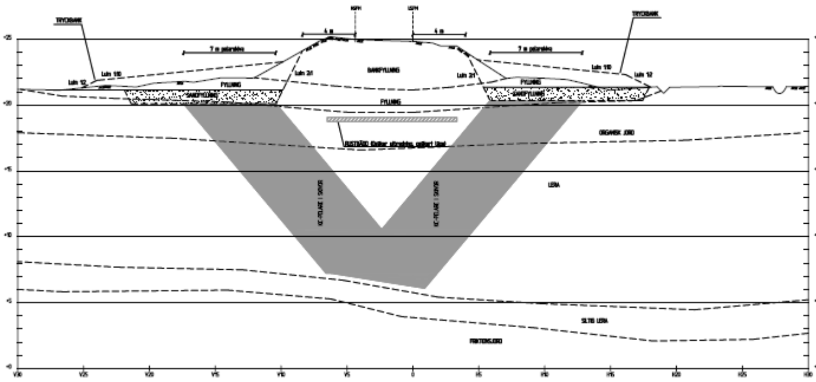
Installation of subgrade strengthening under an existing track and undergoing railway operation is a demanding action. Requirement for comprehensive preparation is obvious and there are many steps that have to be done very carefully and in advance. The following guideline gives an overview of issues that are important to pay attention to:

- Geotechnical condition and investigations, test installation of lime cement columns
- Design of strengthening with inclined lime cement columns
- Measurements plan and safety precautions under installation of inclined strengthening
- Possible restriction on train speed and axle loads during installation under the track
- Preparation of construction site
- Machinery and tools for inclined lime cement columns
- Supervision under installation of subgrade strengthening
- Follow up after installation of strengthening

3.2. Technical requirements for subgrade reinforcement with inclined columns

No	Requirements to be met	Remarks
1	**Geotechnical condition and investigations, test installation of lime cement columns** Before full scale installation of inclined lime cement columns starts there is always need for comprehensive geotechnical investigations. • Soil properties under existing embankment and natural soil on both sides of embankment must be investigated. Besides classical investigations like drilling and sampling geophysical seismic tomography is recommended since it can in a better way assess properties under operated track and embankment. The figure bellow shows results of seismic tomography for soil conditions under embankment and on the side with natural soil. • Properties of dry mixed soil and final binder recipe have to be assessed. Normally a number of laboratory tests are performed where natural soil is mixed, increase of strength is followed and design shear strength is compared to reach the desirable safety factor of the structure. • Before the actual installation of strengthening under the existing railway embankment, a test installation close to the embankment is recommended. This test installation gives information about the best installation procedure. Usually samples are taken to control if the strength of mixed columns match design assumptions.	***Basic input information***

No	Requirements to be met	Remarks
		
2	**Design of strengthening with inclined lime cement columns** Design of strengthening with inclined lime cement columns has to give clear directions how the work in the field shall be performed. Stability calculations have to show that strengthening geometry and designed strength of lime cement inclined columns reach required safety factor of designed strengthening.  After calculation the geometry of strengthening including number of columns in one wall, inclination and volume of cement/lime mixed per cubic meter of column are decided. The design documentation has to produce a work order showing procedure for installation of each particular wall which should be	***Technical design considering all stages of strengthening***

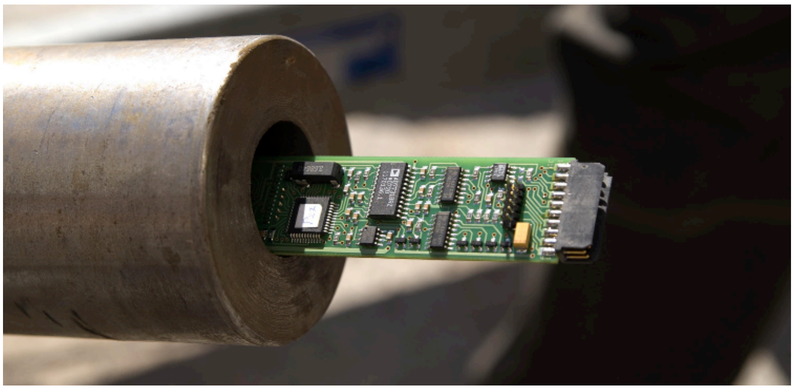
No	Requirements to be met	Remarks
	suggested with consideration of minimal impact of installation on existing track. In many cases there can occur a need for extra excavations and back fillings to assure smooth installation of strengthening (remove big stones etc.) and secure stability of the existing embankment. The following figures show an example of the design for actual project in Sweden.  	
3	**Measurements plan and safety precautions under installation of inclined strengthening** It is important to prepare a measurements plan and a list of safety precaution before start of any excavation close to the existing track and before installation of subgrade strengthening. The purpose of this is to assure full control on a construction site, with the aim to restrain any hazards for train operation on the track. The most complicated sections should be instrumented and a plan for	***Safety arrangement under execution of installation***

<table>
<tr><th>No</th><th>Requirements to be met</th><th>Remarks</th></tr>
<tr><td></td><td>measurements be established. There is always a need to prepare a time table for all measurements and monitoring in relation to the progress of strengthening installation. Measurements plan should consist of the following items:

• Geotechnical related measurements (embankment and subsoil)
o settlements
o pore pressure
o movements of existing embankment-inclinometers
• Monitoring of track
o settlements, elevation of track/tracks and crest
o measurements of twist
• Assessment of critical values for each particular project (track) that indicate limit displacement and twist for track/tracks during construction and clear directions for measures that have to be taken in case limit values are reached.</td><td></td></tr>
<tr><td>4</td><td>Possible restriction on train speed and axle loads during installation under the track

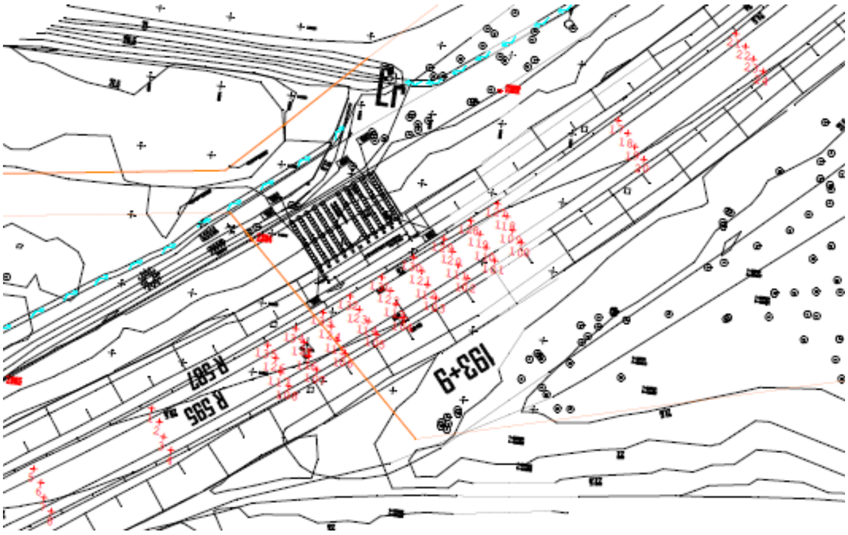
It can be necessary to accept restrictions on train speed and in some cases on axle loads during installation under operated track. It is necessary to assess risks for railway operations if traffic is maintained. Lower train speed and loads decrease dynamic influence on subgrade which is weaker in the time of installation of lime cement columns. There is an experience that even a decrease of allowable speed to 30 km/hour is more acceptable than complete closure of the line for railway operations. It can be profitable to avoid transport of very heavy goods trains for period of strengthening installation. Decision depends on local conditions, embankment height and acceptance of risk.</td><td>Speed axle loads restrictions</td></tr>
</table>

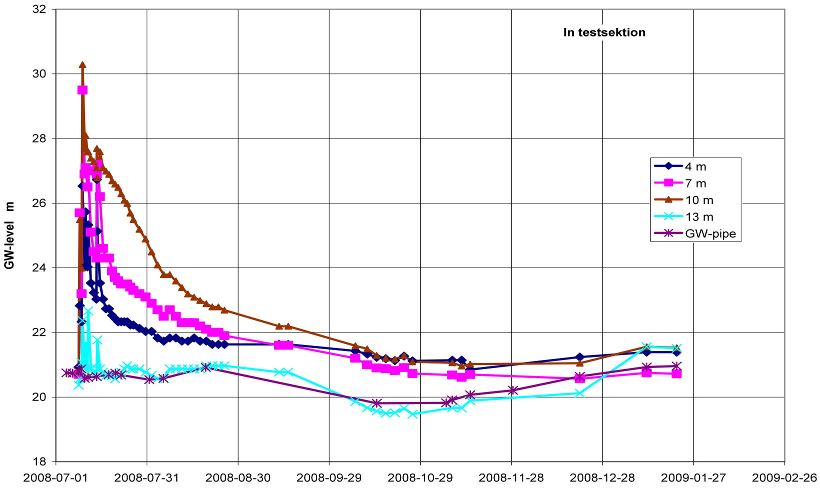
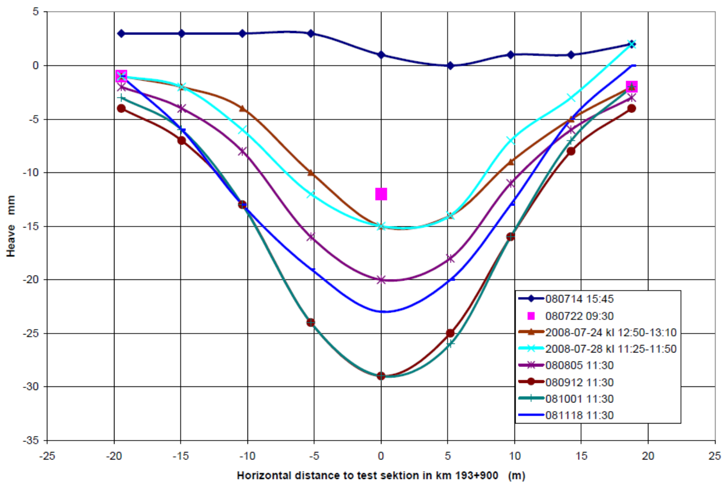
No	Requirements to be met	Remarks
5	**Preparation of construction site** In many cases the place where subgrade strengthening is required is far away from public roads. Thus a special access road has to be constructed as a first step of the project. Mixing machines and heavy trucks need safe transport so the working road must be designed accordingly. Dry mixing method is suitable for soft soils like clays and peat without big stones. If one expects big stones (bigger than 10 cm) those layers have to be excavated and replaced with sand. To reach the required lengths of columns under existing embankment sometimes local (zone) excavation into the embankment is required. Excavation of existing embankment must be carried out in a limited extension, under professional supervision, and for as short time as possible. Any open pit into the embankment has to be immediately refilled by sand, not to hazard stability of operated railway embankment. Since an inclined installation is going to be carried out the mixing machines need to work from very even and horizontal plane. The best result can be obtained if a plane surface is formed by a layer of sand.	***Construction site***
6	**Machinery and tools for inclined lime cement columns** Installation of inclined lime cement columns in a straight wall is a complicated task and there is need for detailed preparation of machines (rig) and tools for this type of dry soil mixing. The mixing tool has to manage continuous mixing and producing homogenous columns even in inclined direction. Figure below shows typical mixing tool used for installation of inclined lime cement walls in Sweden.	***Special tool and machinery***

No	Requirements to be met	Remarks
	 Position of rig during the installation of each column is very important in all directions. It is not an easy task because the rig can be longer than 15 m, and to get the desired results, inclined drilling and mixing needs to be carried out very carefully and under continuous control. Inclination can be measured and controlled using electronic devices mounted on top of mixing tool as can bee seen in the next picture.  Since in many cases there is a need to perform strengthening like wall consisting of individual lime cement columns. The overlap positioning of each column is very important. In the next figure is shown how distance to the next column was controlled. In full scale project there is a need for development of measurement technique that can efficiently and quickly assess position of each column in the wall.	

No	Requirements to be met	Remarks
	 All modern dry mixing machines record information about drilling (pressure) during the time the tool goes down. After that the quantity of mixed lime and cement per meter of column or cubic meter of mixed soil are recorded. This is usually performed by the contractor and records are kept available for future control of column quality. All these data are important after the strength of mixed soil in column is controlled and compared with designed values.	
7	**Supervision under installation of subgrade strengthening** Any strengthening of subgrade under operational railway brings certain risks for the track. Therefore it is important to control track movements very carefully and be ready to limit or stop operation in case limits values are reached. Regarding the track the most important is the monitoring of twist to prevent the risk of derailment. The following picture shows measurement of twist during installation of lime cement columns walls.	***Control of track and surrounding under installation***

No	Requirements to be met	Remarks
	 Another important measurement focus is the control of track displacement. For this reason a number of measurement points on the track (sleepers) and crest have to be assessed. An example of such points is indicated in the next figure. Also the behaviour of the embankment and the subgrade has to be supervised during strengthening work. Continuous measurements of settlements, pore pressures and displacements of the embankment give information about the condition of the railway substructure and subsoil. Again in case agreed limits are reached or even exceeded, precaution measures have to be taken. There may be needs for either limit or stop installation of strengthening or limit train operation for a certain time. There is then a need to repeat measurements and evaluate the behaviour of the whole structure, before full train operations and installation of lime cement columns can continue. Special caution has to be taken during work close to the operated railway as regards safety for workers and machinery. In normal cases an approved and appointed person/persons is/are assigned. They have a responsibility for people and machines that	

No	Requirements to be met	Remarks
	carry out installation of strengthening not to interfere with trains which can in worst- case scenarios may have very bad consequences. Safety on the construction site has to be guarantied for the entire strengthening work. 	
8	**Follow up after installation of strengthening** Under strengthening of subgrade using deep mixing methods a large volume of lime, cement and possible pressured air are inserted to the subgrade. This change of volume is usually followed by change of track elevation. This elevation is afterward followed by settlement that can take long time. This time depends on soil properties and the time needed for excess pore pressure to dissipate. Follow up after installation of strengthening is important since there is a need for an estimation of possible track levelling. The total time for measurements can be assessed according to the demand indicated by the development of pore pressure dissipation. The figure below shows an example of pore pressure measurements that started before installation of lime cement walls and continued more than half year after that. There is obvious the dissipation of the pore pressure in period June 2008 (installation of lime cement column walls) until the last measurements in	***Work and measurements after installation of strengthening***

No	Requirements to be met	Remarks
	January 2009  It is recommended to continue with measurements of the track described in No 7. Information about track settlements are obtained and again track levelling can be planned. The figure bellow shows an example of the development of track settlement. The figure shows the development of sleeper settlements in longitudinal direction of the track. A total distance of 40 m has been measured. The development of measured settlements matches very well the measured pore pressures. Settlements of track ceased in accordance to pore pressure dissipation.  	

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EN 1991	**Eurocode 1: Actions on Structures**
EN 1997-1	**Eurocode 7: Geotechnical Design – Part 1: General Rules**
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Ruin, M. 2009	Provinstallation av lutande KC-pelare in under bank i Torp, Södra Stambanan, Norrköping-Linköping
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