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Mehdi Bahrekazemi
Royal Institute of Technology, Stockholm, Sweden

Anders Bodare
Royal Institute of Technology, Stockholm, Sweden

Bo Andréasson
WSP Sweden AB, Gothenburg, Sweden

Alexander Smekal
The Swedish Rail Administration, Borlänge, Sweden

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MITIGATION OF TRAIN-INDUCED GROUND VIBRATIONS; LESSONS FROM THE LEDSGÅRD PROJECT

Mehdi Bahrekazemi
Royal Institute of Technology
Stockholm, Sweden
kazemi@kth.se

Anders Bodare
Royal Institute of Technology
Stockholm, Sweden
bodare@kth.se

Bo Andréasson
WSP Sweden AB
Gothenburg, Sweden
bo.andreasson@wspgroup.se

Alexander Smekal
The Swedish Rail Administration
Borlänge, Sweden
Alexander.smekal@banverket.se

ABSTRACT

Ground vibrations due to train traffic on ground surface railways built on soft soil can cause annoyance to people, disturb the function of sensitive machinery in nearby buildings and increase the maintenance costs of the track. At low frequencies (< 20 Hz) the level of vibrations is highly dependent on train weight and speed. This issue must be considered in the design of new railway lines or upgrading old ones.

In 1997, shortly after inauguration of the X-2000 high-speed passenger trains between Gothenburg and Malmö in the southern Sweden, extremely high vibration levels were reported in the railway structure, nearby soil and the catenaries at the Ledsgård site and other locations along the newly built ¨West Coast Line¨. In order to mitigate the vibrations and allow the trains to run at their design speed of 200 km/h, soil stabilization using the lime-cement column method was carried out in summer 2000. Measurements before and after the countermeasure showed that, vibrations in the track at maximum speed (200 km/h) were reduced by factor of ten or more. The paper presents the soil stabilization project and some results from the measurements carried out in connection with it.

INTRODUCTION

High-speed trains are gaining more popularity as an effective way of transportation around the world. In Sweden like many other European countries development of high-speed railways has progressed rapidly during the last two decades. While several new lines have been opened some existing lines have been upgraded for higher speeds and axle loads. In this frame work new lines are being designed for a maximum speed of 250 km/h and the highest maximum axle load of 30 ton.

One of the problems that may arise from higher train speed and axel loads is excessive vibrations in the track and surrounding ground. Such vibrations in the track may result in high maintenance costs and in very severe cases they can endanger the safety of the train operation. In addition the environmental ground vibrations from train traffic cause annoyance to people as well as disturbance in function of sensitive equipments in nearby buildings.

Trains moving on surface railways resting on soft ground cause vibrations at frequencies primarily below 20Hz (Bahrekazemi & Bodare, 2003). Therefore reduction of vibrations especially in the low frequency domain may be necessary in order to secure the required track capacity.

In April 1997, shortly after opening some parts of the West Coast Line in Sweden, excessive ground vibrations were reported as the high-speed X2000 train passed the Ledsgård area at 200km/h. The site known as Ledsgård is situated approximately 25 km south of city Gothenburg on the “West Coast High-speed Train Line” connecting Gothenburg and Malmö in Southern Sweden.

Following reports of very high vibrations levels, thorough investigations were initiated by the Swedish National Rail Administration (Banverket) in order to investigate the cause of the problem. Meanwhile the speed of the trains was reduced to 130 km/h from the design speed of 200km/h. Geotechnical and seismic measurements at the site suggested that the high vibrations were due to very soft underlying soil (Adolfsson et al., 1999). The soil profile of Ledsgård consists mainly of organic soil (gyttja) below which a soft clay with gradually increasing shear strength to a depth more than 50 m is found (Adolfsson et al., 1999). The velocity of the shear waves in the organic layer, which in the worst section is about three meters thick, is as low as 40 m/s and therefore a passing train at a speed of about 200 km/h (55 m/s) is running at a speed grater than the shear wave velocity of that layer. The speed of the train is also close but less than the critical speed of the track (Madshus & Kaynia, 2000).

In order to reduce the train-induced ground vibrations in the track and at distance from it, three links must be considered. These links are generation of the vibrations at the source, their propagation through the media, and their interaction with the structure. At each of the links, countermeasures can be taken to reduce the vibrations and their effects. At the Ledsgård site it was decided to modify the source with stabilization by lime-cement columns under the track. This was adopted as the method was considered optimal and more economical than the alternative ones. The alternative methods considered were building a concrete deck on concrete piles or a very stiff concrete beam under the embankment. Besides increasing the stiffness of the underlying soil and thereby decreasing the amplitude of the vibrations in general, higher stiffness of the underlying soil results in much lower vibration levels in case of high-speed trains compared to the situation before the countermeasure. This is due to fact that in case of improved track the speed of the train will be much lower than the critical speed of the track (Fryba, 1999).

SOIL STABILIZATION METHOD AS COUNTERMEASURE

As illustrated in Fig. 1 soil stabilization can be used in different ways in order to mitigate ground vibrations from train traffic. Lime-cement columns, for example, can be used either to improve the soil directly under the embankment or as an in-filled stiff trench as shown in the middle part of the same figure. If used under the embankment, the stabilized soil has two mitigation effects. The first effect is due to the increased stiffness of the underlying soil that in turn will result in reduced vibration amplitude even in case of low speed trains. The second effect which is more important in case of high-speed trains is due to the fact that higher stiffness of the underlying soil results in higher critical speed for the track (see above). These aspects of the method are explained in more details in the following sections. The in-filled trench on the other hand works as a barrier in the path of propagating waves and therefore must have a depth which is comparable with the longest wave length (Ahmad & Al-Hussaini, 1991).

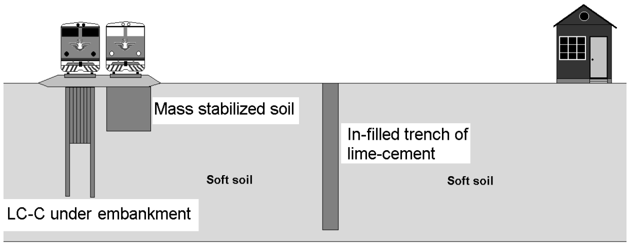

Fig. 1. Different ways of using soil stabilization as countermeasure against train induced ground vibrations, (Bahrekazemi & Bodare, 2003).

Lime-Cement Column Method

Soil stabilization using lime-cement mixtures is today a well-developed technology. Basically there are two methods of adding the additive to the soil, i.e. the wet and the dry method. In the dry method, which is the method usually used in Sweden, the binder is forced into the soil as a dry powder using compressed air. First a rotary device is forced into the soil to the depth that should be stabilized. Then at the same time that the rotary device is pulling out of the soil the dry binder is mixed in the soft soil by compressed air. The binder is forced into the soil through a hole just above the mixing device. The diameter, centre to centre distance and length of the lime-cement columns are determined according to the desired performance. This method is widely used in Sweden for stabilizing soft ground under roads and railways (see Fig. 2) as well as slope stabilization when trenches are to be cut in soft soil.

Fig. 2. Installation of lime-cement columns in Ledsgård, June 2000, Sweden, (J&W / WSP, 2000).

Ledsgård Site and the Countermeasure Design

The railway track at Ledsgård site consists of UIC 60 rail placed on Panderol rubber pads (10 mm) and concrete sleepers with a spacing of 0.67 m. The thickness of the ballast (crushed bedrock) is 0.5 m of which 0.3 m lies under the sleepers. The total height of the embankment including the ballast layer is about 1.4 m.

Geotechnical investigations at Ledsgård site reveals that there is a pocket of gyttja (organic soil) with a maximum thickness of 3 m underlying an approximately 1 m thick layer of dry crust. The extent of the gyttja pocket is about 200 m along the railway track. A thick layer of more than 50 m clay is underlying the gyttja layer before bedrock is reached (Adolfsson et al., 1999). The gyttja pocket starts at approximately Section 24+150 and continues to approximately Section 24+400. Adjacent to a bridge close to Section 24+400 there is a part where the soil was improved with lime-cement columns in order to limit long-term settlements. The most extensive ground vibrations measured at the site corresponded to the soft gyttja pocket but due to observed settlements all the way back to Section 24+000 improvement was carried out from this section to 24+372, where it was connected to the existing reinforcement at the bridge.

The first 150 m, from Section 24+000, was stabilized with lime-cement columns in a singular pattern as shown Fig. 3. From Section 24+150 to the existing lime-cement columns close to the bridge the columns were installed in a ladder pattern with one longitudinal wall under each rail and transverse walls crossing the longitudinal ones at each 2.0 m. In order to make smooth transition to the existing reinforcement at the bridge area and for settlement reasons every second column in the longitudinal walls extend to 13 m depth, while the other columns in the longitudinal walls were only 7.0 m long. The columns in the transverse walls were 6.0 m long. The soil stabilization measures at the Ledsgård site were designed by WSP Civil, Gothenburg (formerly J&W).

The amount of binder was 150 kg/m^3 in the "ladder" part (from Section 24+150 to the old stabilization part) consisted of the components unslaked lime and cement in ratio 25:75. For the parts with singular columns, the amount of binder was 120 kg/m^3 also with binder combination ratio 50:50.

In this phase of the project only the western track, which had been recently built and showed the largest vibrations, was improved. The work started in May 2000 lasting about three months excluding the two weeks for test columns that were installed adjacent to the track in order to test the quality of the material in the field. The traffic was disturbed between July 9 and July 31, 2000. Figure 2 shows the columns being installed under the western track with a commuter train passing on the eastern track.

During the installation of the lime-cement columns a substantial heave was observed in the neighboring track. This was not surprising considering the substantial amount of lime-cement mixed into the ground. The columns were installed from a working bed consisting of gravel that was later removed to expose the tops of the columns (Holm et. al, 2002).

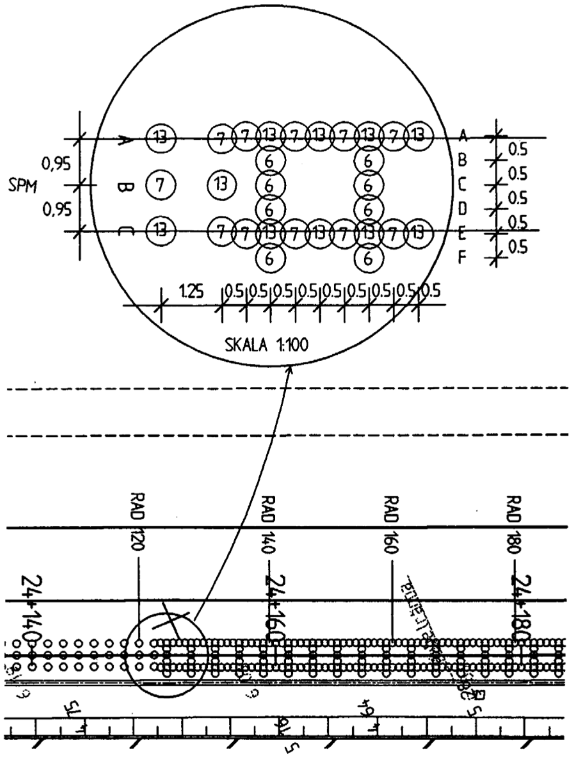

Fig. 3. Layout of soil improvement with lime-cement columns at Ledsgård. Also showing the transition at section 24+150. Column length below rail level is given by figures inside circles, (J&W / WSP, 2000).

Numerical Analyses. In order to design the countermeasure in an effective way a numerical model can be used. Such a model has been used by the authors to evaluate the countermeasure and study the effect of changes in different parameters. Adolfsson et al. (1999) used the finite difference code FLAC3 while Bahrekazemi and Bodare, (2001) used the finite element code ABAQUS for this purpose.

The three-dimensional FEM model described here (ABAQUS) as shown in Fig. 4 consists of the rail, sleeper, embankment, and five layers of soil.

Although some aspects of the ground vibrations due to train traffic are associated with the summation and interference of the response to multiple axle loads, measurements done at Ledsgård reveal that in order to find the maximum particle displacement during the passage of a train it is not necessary to consider all bogies. This approximation is especially appropriate when the speed of the train is lower than the critical speed of the track. This means that in order to find the maximum deformation in the track due to train passage it is enough as a good approximation to consider only the heaviest wheel and not the whole train.

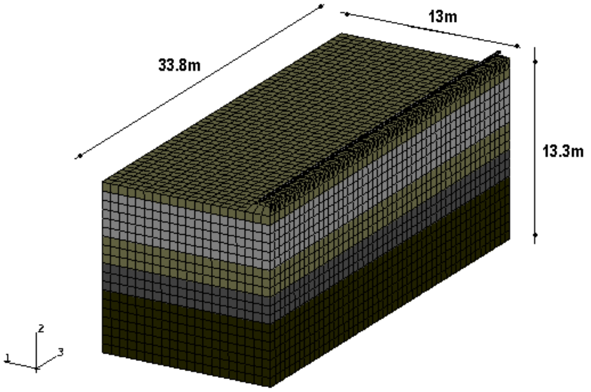

Fig. 4. Three-dimensional FEM model in ABAQUS.

For the purpose of simulation, the moving load is directly applied on the rails that are connected to the sleepers via springs and dashpots. As the load moves on the rail, it is distributed on different sleepers.

Material properties of the different parts, for both improved and unimproved soil must be determined in order to be able to use a numerical model. The important properties are the E-modulus or G-modulus, Poison's ratio, damping ratio, and the density of the material. Some of these parameters can be estimated with good accuracy, while others should be determined through laboratory or preferably field tests in order to be reliable. If laboratory results are used it should be noted that usually field conditions are different from those in the lab and therefore the results must be modified to account for this difference.

The dynamic soil properties at the Ledsgård site have been investigated before (Adolfsson et al., 1998) and (Hall, 2000). Furthermore, unconfined compression tests on untreated soil samples resulted in undrained shear strength of 20kPa and an E-modulus of 1.1MPa. The compression at failure was approximately 1% with a brittle failure mode (see Fig. 5). The unconfined compression tests of the treated samples showed a very good effect of the treatment. Laboratory test results after 162 days showed that while the undrained shear strength was improved by a factor of 20 times, the E-modulus had been improved about 100 times after improvement of gyttja by 150 kg/m^3 lime-cement mixture with a proportion of 25:75 (see Fig. 6). The E-modulus measured in the tests was measured by high strain methods which give lower modulus than the low-strain modulus usually used in wave propagation simulations. While the low strain modulus can be determined by measuring the propagation velocity of waves in the material, estimated dynamic properties based on the high-strain values were used for the purpose of this project. In order to use the parameters for the model they should be modified for the actual strain in every part of the model. The material properties as used for different parts of the three-dimensional model are presented in Table 1.

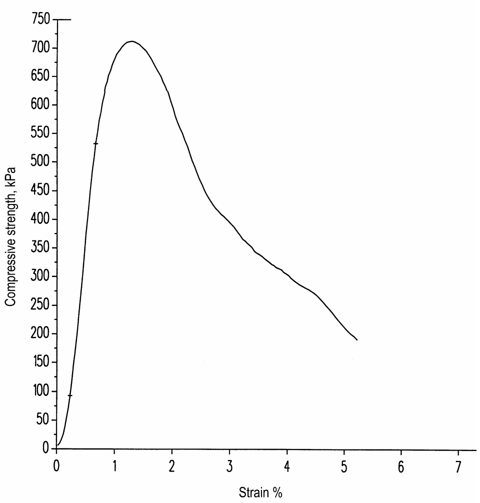

Fig. 5. Unconfined compression test of laboratory mixed sample of lime-cement stabilized soil.

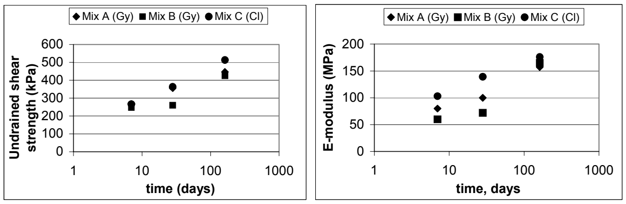

Fig. 6. Development of shear strength and E-modulus of lime-cement stabilized gyttja (GY) and clay (Cl) with time. The binder is 150 kg/m^3 lime/cement in proportion 25/75.

Figure 7 shows the deflection introduced to the track and surrounding ground before and after soil stabilization. Some further simulation results as well as corresponding measurement results are presented in Fig. 8. After validating the FEM model using measurement results, the model was used to perform a parameter study from which some results are presented in Fig. 9. The improvement ratio introduced in this figure is the ratio between the modulus of the treated soil to that of the untreated soil.

Table1. Dynamic material properties as used for the three-dimensional ABAQUS model. The density of the lime-cement columns is almost the same as the soil.

Layer	Depth (m)	ρ (kg/m^3)	Cs (m/s)	Cp (m/s)	E (MPa)	G (MPa)	ν	Damping ratio, ξ%
Sleeper	0.0-0.25	2400	2331	3633	30000	13043.48	0.150	
Embankment	0.25-0.95	1900	233	436	268		0.300	4-5
Crust	0.95-1.65	1700	60	300	18	6.09	0.479	4-5
LC-C					70-700		0.300	4-5
Gyttja	1.65-4.9	1260	44	570	7	2.34	0.497	4-5
LC-C					70-700		0.300	4-5
Clay1	4.9-6.85	1450	49	1050	11	3.67	0.499	4-5
LC-C					110-1100		0.300	4-5
Clay2	6.85-8.8	1450	56	1050	13	4.34	0.499	4-5
LC-C					110-1100		0.300	4-5
Clay3	8.8-13.3	1500	75	1050	25	8.35	0.497	4-5
LC-C					150-1500		0.300	4-5

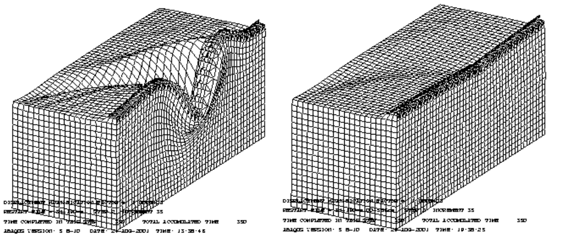

Fig. 7. (a) Deflection before LC-C,(b) Deflection after LC-C columns using the 3-D FEM model.

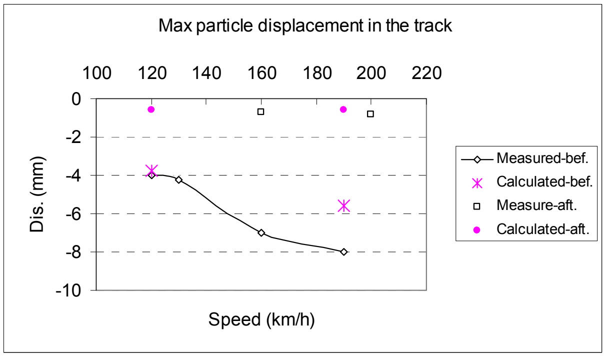

Fig. 8. Simulated and measured maximum displacement in the track before and after the LC-C at Ledsgård.

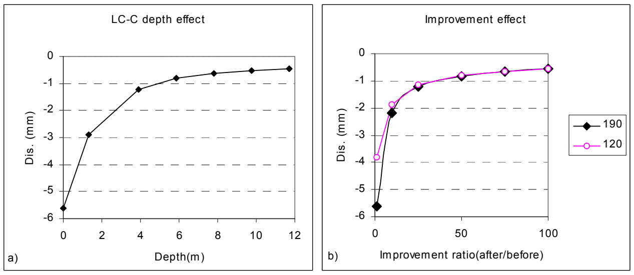

Fig. 9. (a) Effect of LC-C depth, (b) improvement ratio and train speed on particle displacement at Ledsgård.

Vibration Measurements. An extensive measurement program has been carried out. Measurements of track and ground vibrations before and after the soil improvement were part of this program that was carried out by different groups including the Royal Institute of Technology in Stockholm (KTH), (Bahrekazemi et al., 2001), the Swedish National Rail Administration, Banverket, the Swedish Geotechnical Institute, SGI (Adolfsson et al., 1998), and J&W/WSP (2000).

Figure 10 and Fig. 11 show the sensors used by KTH for these measurements before and after the soil stabilization respectively.

Figure 12 shows how the peak to peak amplitude of the particle displacement has been decreased after the countermeasure for trains running at different speeds. As it is shown in the figure while the peak to peak amplitude was reduced by a factor about 5 for trains running at low speeds, it was reduced about 15 times for high-speed trains. This was expected since the dynamic amplification due to the critical speed effects was removed from the vibrations.

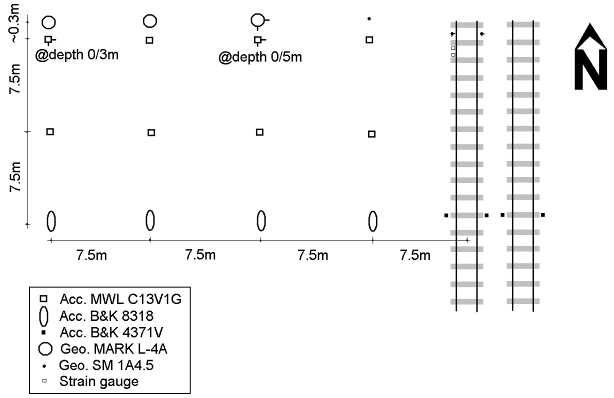

Fig. 10. Instrumentation plan, May 2000, Ledsgård, Sweden

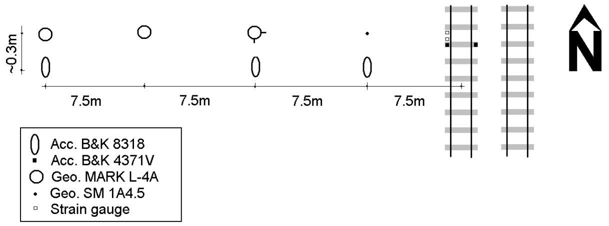

Fig. 11. Instrumentation plan, Dec. 2000, Ledsgård, Sweden.

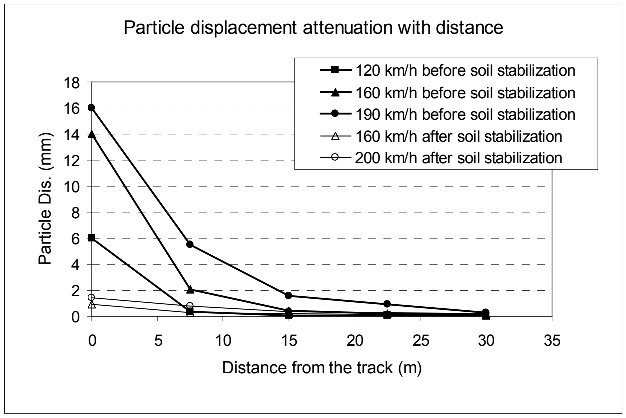

Fig. 12. Attenuation of maximum particle displacement (peak to peak) with distance from the mid-point of the west track for different train speeds before and after soil stabilization.

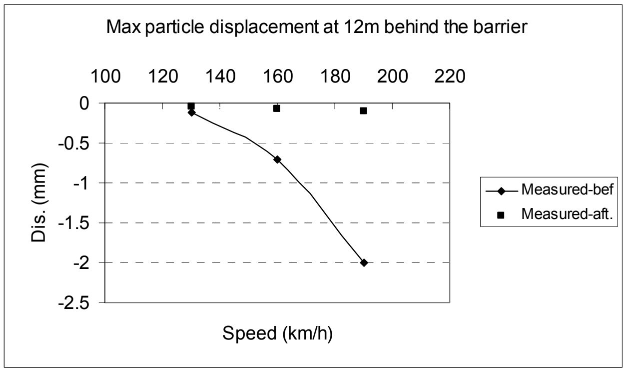

Fig. 13. Barrier effect of LC-C. Here LC-C under the west track is considered as in-filled trench for the east track.

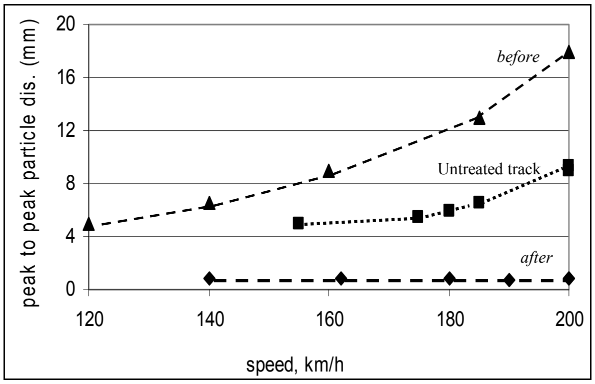

Fig. 14. Dependence of maximum peak to peak particle displacement to train speed.

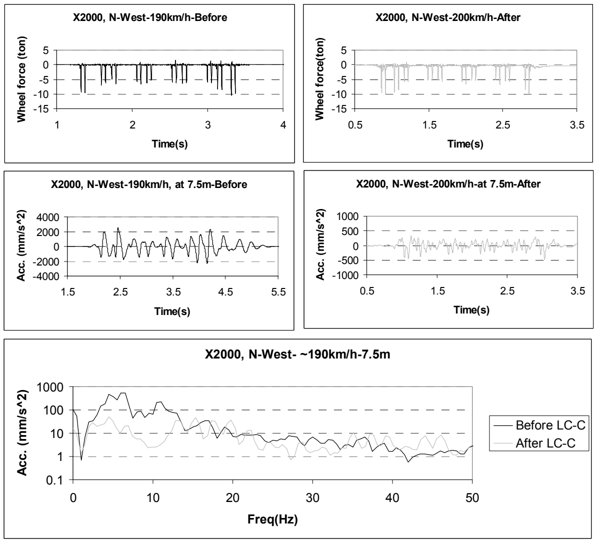

Fig. 15. Comparison between before and after soil stabilization in time and frequency domain.

Similar measurements shown in Fig. 13 suggest that despite the fact that soil improvement was only carried out under the western track, vibrations to the surroundings were mitigated even when trains passed on the untreated east track. This is thought to be partly due to the fact that the lime-cement column walls under the west track worked somewhat as a barrier (in-filled trench) in the path of vibrations from the east track (Bahrekazemi et al., 2001).

Dependence of the maximum particle displacement to the train speed is shown in Fig. 14. It is seen from the figure that the peak to peak particle displacement increases dramatically as the train speed approaches 200 km/h. This speed is very close to the Rayleigh wave velocity of the subsoil and the critical speed of the track which was estimated at about 230 km/h (Madshus & Kaynia, 2000).

Figure 17 presents a comparison between ground vibrations on the ground at 7.5 m from the midpoint of the track before and after the countermeasure both in time and frequency domain. It is seen from the figure that in the low frequency domain (where the major part of the energy exists) the countermeasure has effectively reduced the vibrations.

Besides performing measurements during passage of different trains, the track response was measured both before and after the countermeasure using Banverket's Track Loading Vehicle, TLV (Smekal & Berggren, 2002). The TLV has a weight of 49 ton and has three hydraulic cylinders, two vertical and one lateral, each capable of a maximum static force of 150kN and dynamic excitation between 0 – 200 Hz. The track behaviour under the loading was mainly measured with accelerometers double integrated to obtain displacements (see Fig. 16). As it is seen from the figure, the receptance is reduced considerably after the improvement. It is also observed from the figure that in the low frequency domain the change in receptance is much more pronounced compared to the high frequency window. On the other hand as mentioned earlier the major part of the energy of vibration is in the low frequency domain and this is where the stabilization method is most effective.

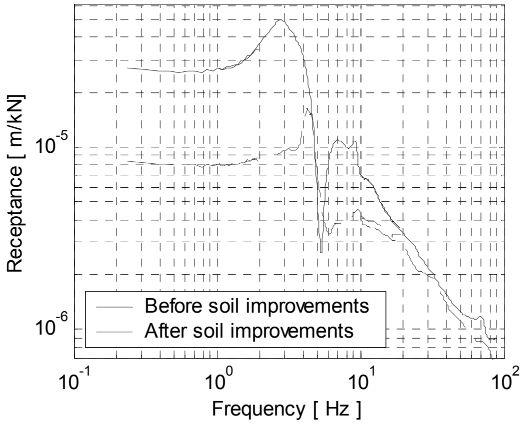

Fig. 16. Receptance curves for west track before and after the lime-cement soil stabilization at Ledsgård site.

Comparing early measurements of the reinforced track six weeks (September 2000) after soil improvement with the December 2000 measurements (4.5 months after the countermeasure) show that the vertical vibrations reduce with time. The measured vertical particle displacement amplitude was 1.0 mm in September 2000 reducing to 0.8 mm in December 2000 for similar train passage. This indicates that the major portion of the mitigation effect of the countermeasure is achieved a within a few weeks after the installation of lime-cement columns.

Costs. The total cost of the project was about 601,000 €. In Fig. 17 the cost for different parts of the project are presented. Observe the minor part of the lime-cement installation compared to the total costs of the project. This implies that if a method is developed so that the soil stabilization can be applied without removing the track, the costs would decrease with about 50% according to the experience from the Ledsgård project.

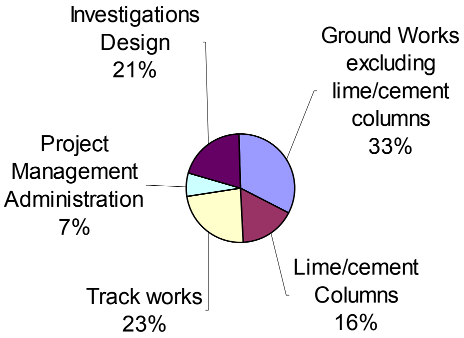

Fig. 17. Distribution of costs for the Ledsgård project (Holm et al., 2002).

DISCUSSION

Frequency spectrum of particle acceleration in *Fig. 15* shows that the major part of the energy of vibration is below 20 Hz. The highest frequency carrying the energy is even lower if the particle velocity or displacement is considered (below 10Hz). Figure 12 shows attenuation of the maximum peak to peak particle velocity and particle displacement with distance from the mid-point of the west track before and after LC-C stabilization of the soil. It is also seen in Fig. 12 that the effect of the countermeasure becomes less at large distances from the track.

Figure 8 compares the maximum particle displacement obtained from measurements and simulations for different train speeds. It is seen from the figures that the agreement between simulation and measurement is good in all cases. Furthermore it can be seen that both simulation and measurement indicate that after soil improvement by lime-cement columns, the maximum particle displacement is not changed so much by train speed while before stabilization, train speeds close to critical speed of the track results in much higher particle displacement.

Figure 9a shows the effect of the lime-cement columns depth on the maximum vibration amplitude obtained from a parameter study using the 3D-FEM model. The figure shows that there is an optimum depth for the columns.

It is implied by Fig. 9b that the improvement effect is not so sensitive to the stiffness of the improved soil as long as the improved stiffness is in the range higher than a certain limit. This limit can be considered at about 25 times for the curve shown in this figure. As it is seen from the figure the effect of speed becomes unimportant at higher stiffness. This is confirming the hypothesis that train speeds near the critical speed of the track-ground system or Rayleigh wave speed of the underlying ground would result in amplification of the ground vibrations. In other words, if the train speed was far from either of these speeds, the lime-cement countermeasure would have the same effect on ground vibrations due to high-speed trains and normal-speed trains. Another important issue that can be concluded is that there is an optimum improvement ratio (shear modulus after/ shear modulus before) beyond which no significant further reduction in the maximum amplitude of vibration will be obtained.

CONCLUSIONS

As conclusion it can be stated that soil stabilization by lime-cement columns under the embankment is effective as a countermeasure against train induced track/ground vibrations. Using this method in Ledsgård, the particle displacement of vibrations were reduced by a factor of approximately 5 at low train speeds and up to about 15 for the high-speed X2000 train running at about 200km/h.

The mitigation effect of the method reduces with distance from the track. Therefore, this issue should be considered if vibrations must be mitigated at long distances from the track.

Furthermore it was shown that in-filled trenches made of lime-cement columns are somewhat effective as barriers reducing the vibrations behind the wall.

As long as the material properties of the stabilized soil is concerned, the experience from the Ledsgård project shows that assuming that the stiffness of the stabilized soil (E-modulus) will be increased with the same ratio as its strength (undrained shear strength) is a conservative assumption.

Although the mitigation effect of lime-cement soil stabilization against train-induced ground vibrations increases with time, the major part of the reduction in the particle displacement amplitude is achieved only a few weeks after the installation of lime-cement columns.

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