REDUCTION OF TRAIN VIBRATION BY DEEP STABILIZATION

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ABSTRACT - Train traffic can cause environmental vibrations close to the track. In this study environmental vibrations and deep stabilized structures under train tracks were analyzed using numerical methods. The results of the analysis indicate that deformations decreased under the track, but environmental deformations cannot be estimated based on these results. Soil and stabilized columns interact and vibration energy is transferred horizontally and can increase environmental vibrations. In order to decrease environmental vibration, the stiffness of deep stabilization should be higher as usual, then interaction between columns and soil will be decreased and the environmental vibration will be lower.

RÉSUMÉ – Le trafic ferroviaire peut causer des vibrations aux environs des rails. Dans cette étude, les structures de stabilisation en profondeur au-dessous des rails, à l'aide desquelles les vibrations peuvent être réduites, ont été recherchées numériquement. Les résultats de l'analyse indiquent une réduction des déformations au-dessous des rails, mais on ne peut pas fonder l'estimation des déformations environnementales sur ces résultats. Le sol et les piliers stabilisés sont interactifs et l'énergie des vibrations est transmise horizontalement augmentant des vibrations environnementales. Afin de les réduire la stabilisation en profondeur devait être plus rigide que d'habitude. Alors, l'interaction des piliers et le sol va être réduite et la vibration environnementale diminuée.

1. Introduction

The popularity of safe, environmental-friendly rail travel has increased in Finland and many other European countries in recent years. Rail traffic, however, causes noise and vibrations in the environment surrounding railway tracks. Vibration problems are especially evident in areas with soft clay substrates where heavy freight trains run. Because soft clay strata are commonly found in South Finland, which is also densely populated, large numbers of people may experience disturbances caused by vibrations.

The environmental vibration load reaches its maximum dispersion when a train's axle load is exerted on the rails. Moving wheel load deformations are resisted by the stiffness, damping and inertia of the track and its substructure. The combined effect of these results is the dissipation of vibrations into the environment, even if the track was perfectly smooth and even. Typically this bypass frequency is approximately 3-6 Hz. The lowest natural frequency of the soft soil layers and, in particular, the lowest horizontal natural frequency of two-story small house is often within the same frequency area.

In soft soil strata higher frequency vibration loads caused by the condition of trains and rolling stock are dampened in close proximity to the track and are not generally a nuisance to people. The environmental vibration caused by rail-way traffic can be reduced by: influencing the vibration source (1); influencing the track substructure (2); building an isolating structure outside the track or by stiffening structures (3) (Figure 1).

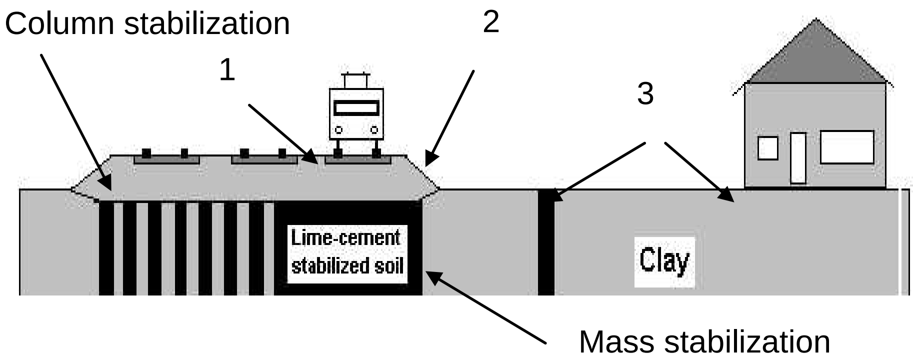

Figure 1. The methods to decrease the environmental vibration caused by railway traffic, for numbers see the text.

The article examines the impact of track substructure stabilization on vibrations dissipated into the environment. There is conflicting data on the impact of stabilization. In some articles stabilization is estimated to reduce the amount of vibration transmitted from the track into the environment by approximately 50% (Madshus 1997, Holm 1999). In Ledsgård, Sweden, quite a significant reduction in environmental vibration was achieved close to the track, but further away the decrease in vibration reduction was remarkable (Holm et al. 2002).

Vibration measurements taken in areas surrounding the stabilized sections (length > 500 m) of the new Helsinki-Lahti railway line showed no measurable decrease in vibration. Passing freight trains were 4000 – 4500 tonnes in weight, 700 – 800 metres in length and with a velocity of approx. 60 km/h. The depth of the soft clay layer and the length of the stabilized columns were generally 10 – 15 m. The shear strength of natural clay was 20 – 30 kN/m^2. The stabilized substructure decreased settlements of the track as planned. Vibration was measured between 20 – 120 m away from the track (The Finnish National Rail Administration 2006).

In this study deep stabilized structures under train tracks were analyzed using numerical methods. Sami Kurkela has described the analysis in detail in his research (Kurkela 2007).

2. Numerical analysis

The numerical analysis was done with FLAC 4.0 Code in the time domain. FLAC Code (Fast Lagrangian Analysis of Continua) is a two-dimensional explicit finite difference computer code developed by the Itasca Consulting Group Inc.

The present problem of train induced cyclic loads is very much a three-dimensional one. Therefore it is not possible to get precise results with the 2D FLAC. As the purpose of the work is clearly delimited to qualitative results and dependencies, this tool was seen to be suited for the analysis. A simple rectangular grid was used. The element size was generally 1 m and it was generally shorter than wave length /8, which is around 6 m at its shortest.

The analyzed model should be as large as possible in order to calculate the vibration as well as possible. The size of the model was limited to the properties of the code and calculation time. The dynamic loading was sine wave normally at 3, 5 or 7 Hz. The amplitude of loading has no significance because the model was linear elastic and the purpose was not to calculate real values but relative displacements.

Boundary settings in dynamic analysis may cause a reflection of the outward propagating waves in the model. The use of larger models can minimize this problem, but this solution leads to a large computation burden. Therefore FLAC offers alternatively types of boundaries for dynamic studies: quiet (absorbing), free field and three-dimensional radiation-damping boundaries. Free field boundaries are depicted below.

Rayleigh damping is commonly used in time-domain programs to provide damping that is approximately frequency-independent over a restricted range of frequencies. In analysis Rayleigh damping can need long calculation time. Local damping is easier in application as no centre frequency range has to be settled. However, it is only well suited for systems with simple waveforms. In material damping the local damping (here 0,03) is suitable for the analysis of simple sine waves. The results of the vibration were calculated from the distance of 30 m and 50 m from the centerline of the track and in the centre of the track.

3. Analysis and results

Mass- and column stabilization structures which increase the stiffness of track substructures were analyzed. At present, only column stabilization was actually used in track substructures. The study also examined mass stabilization structures, as their calculation and analysis was simpler than those for column stabilization and the method could have practical applications in the future. Geometric models and their indicators are shown in Table 1.

Table 1. Geometry of calculation models.

Indicator	Stabilization thickness zp [m]	Clay thickness [m]	Clay thickness under stabilization [m]
8/8	8	8	0
8/12	8	12	4
8/16	8	16	8
10/12	10	12	4
10/16	10	16	6
12/12	12	12	0
12/16	12	16	4

The basic calculations made used stabilization depths of 8, 10 and 12 m, with the corresponding clay depths of 8, 12 and 16 m. Some of the stabilization was extended to hard substrata and others to a specific depth, at which there was clay between the stabilization and the moraine at the bottom of the model. In the calculation models the lowest level was a moraine layer. The embankment height used in the calculation of mass stabilization was 1 meter and in other calculation cases, 2 meters. The soil material values typically found in Southern Finland were used in the calculations. Planning phase values (Table 2) were used as stabilization material values.

Table 2. Material parameters.

	Shear-wave velocity V_s [m/s]	Poisson's ratio	Shear modulus [MPa]
Stabilization	200	0,3	80
Stabilization	300	0,3	180
Stabilization	500	0.3	500
Dry crust	150	0.45	40.5
Embankment	300	0.3	180
Clay 1	40	0.45	2.9
Clay 2	70	0.45	8.8
Clay 3	100	0.45	18
Moraine	500	0.3	500

3.1 Mass stabilization

Natural structural frequencies were calculated in soil stabilization cases. The natural frequency f_{sn} of the homogeneous soil layer and its multiples were calculated according to the following equation (1):

$$f_n = \frac{V_s(2n-1)}{4H} \quad (1)$$

where
n equals the frequency multiple value and
H equals the thickness of the layer (m)

The natural frequency of the layered structure was calculated using the superposition principle. The impact of stabilization thickness on the combined natural frequency of the structure is shown in Figure 2.

The structure's natural frequency was low ($f_{sn} \leq 3$ Hz) when stabilization did not extend to hard substrata. When extended to hard sub-strata, the structure's natural frequency increased rapidly. Based on natural frequency calculations, the natural frequency of the track substructure was nearly always close to the train load frequency (approx. 3–7 Hz). Based on numerical calculations, however, resonance does not appear to significantly increase vibration.

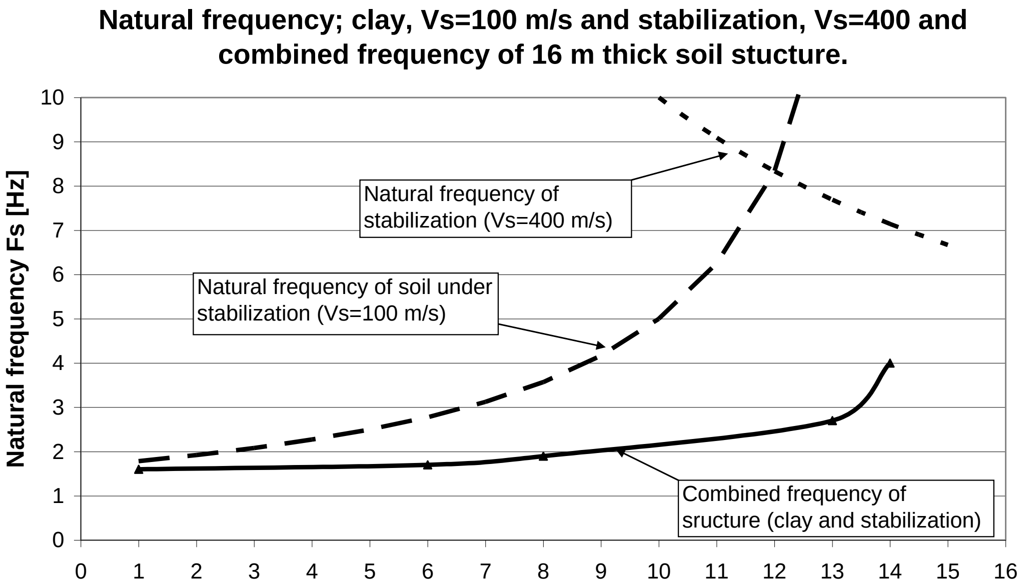

Figure 2. Impact of mass stabilization thickness on natural frequency, with a total structural thickness of 16 meters, stabilization V_s=400 and clay V_s=100 m/s.

At the lowest stabilization strengths (V_s=200 m/s) almost no dampening effect on environmental vibration in stabilized areas was observed (Figure 3).

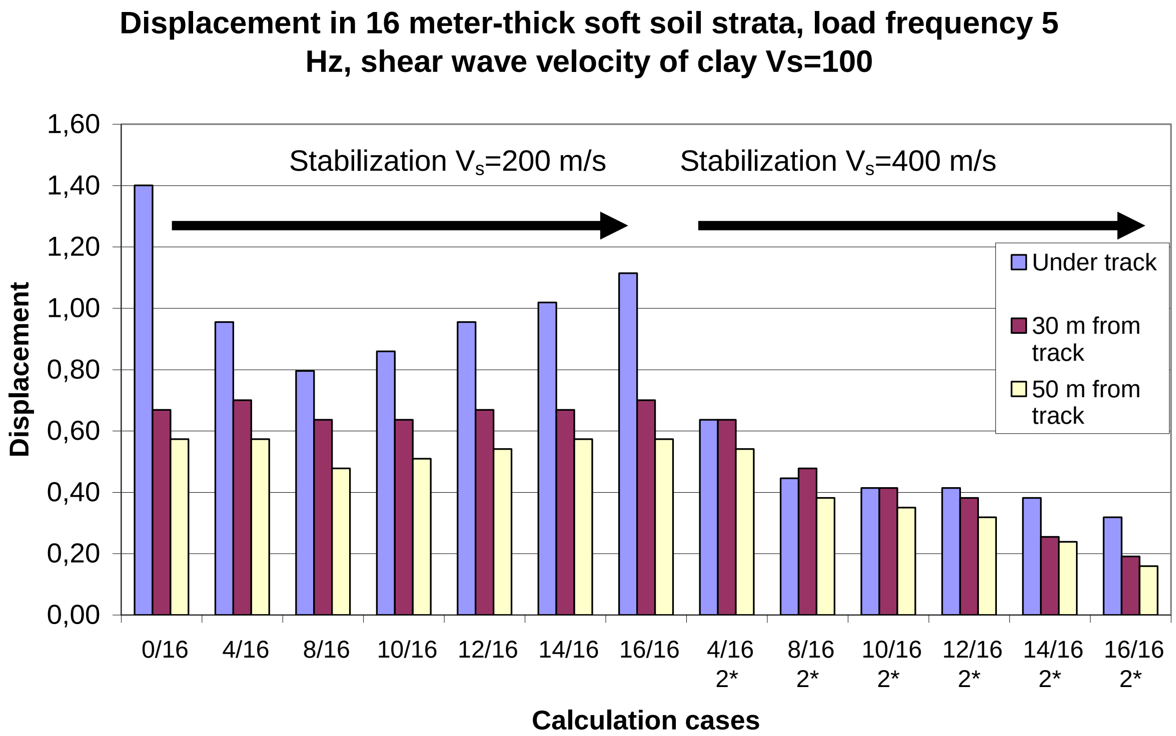

Figure 3. Impact of mass stabilization strength and stabilization depth on displacement in 16 meters thick soft soil strata.

Subtract displacements increase along with an increase in stabilization thickness. In this case the structure will most likely approach resonance. When stabilization and stiffness are increased, displacement levels decrease. Stiff stabilization can reduce vibration effectively if it extends as deeply as possible to hard sub-strata.

Figure 4 provides a more detailed examination of the impact that loading frequency has on environmental vibrations. The natural frequency of this calculation case (10/16) is approx. 2 Hz.

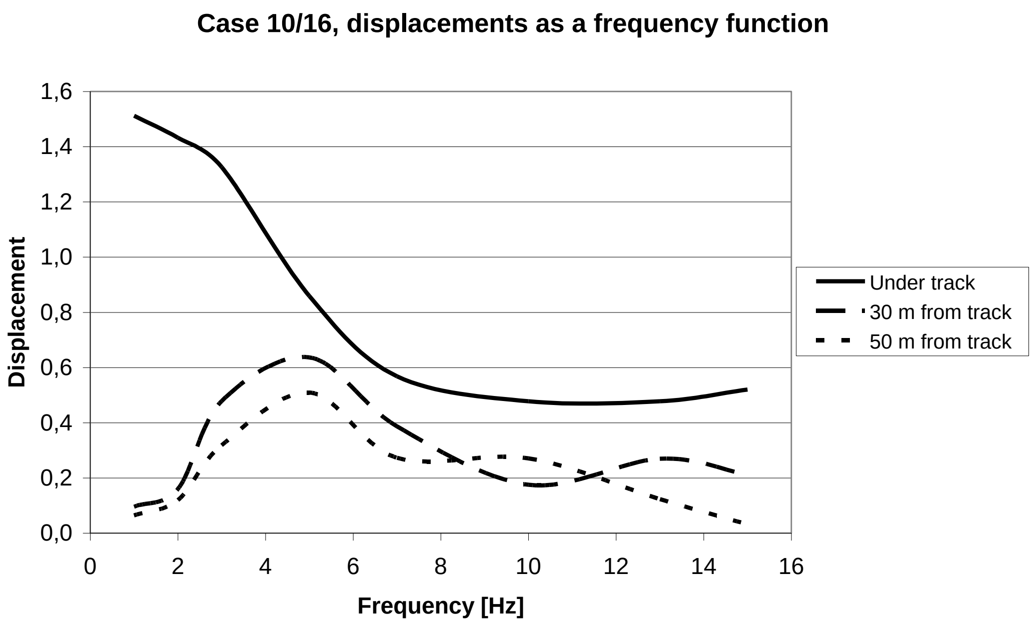

Figure 4. Calculation case 10/16 displacements of mass stabilization as a frequency function.

When the impulse frequency is close to the structure's natural frequency, subtract displacement levels are at their maximum. Vibration levels are low in this kind of environment. When the loading frequency is greater than the natural frequency of surrounding soil layers, displacements under the track decrease while increasing in areas surrounding it. In this case the vibration energy radiates out from the track. As a result, displacements occurring under the track cannot be used to estimate displacements occurring around the track.

3.2 Column stabilization

The natural frequency of column stabilized structures cannot be mathematically determined using simple analytical methods. The natural frequency is assessed based on calculation results. At resonance frequency, displacements are at maximum and the structure’s dynamic stiffness is at minimum.

In column stabilization cases the column diameter was d = 0.6 m and column spacing was e = 1.4 m (c/c). However, because the actual situation occurs in three dimensions, the column size was changed in displacement examinations, taking into consideration the surface areas of columns and the clay between them by calculating the equivalent column diameter (Equation 2).

$$d_{calc} = \frac{\pi d^2}{4e} \qquad (2)$$

d_{calc}	equivalent column diameter
d	actual column diameter
e	column spacing

In calculation models columns were shown as two-dimensional lamina with a width of 0.2 m. In examining the dynamic interaction between the columns and soil columns with an actual column diameter (0.6 m) were used, because the dynamic interaction would not appear correctly when using equivalent columns.

The dynamic stiffness depends on the phase difference at which the vibration waves meet consecutive columns. The phase difference depends on whether the stiffness increases or decreases (Figure 5).

Dynamic stiffness is therefore dependent on loading frequency, column spacing and column diameter. There is usually a phase difference between dynamic stiffness and damping. Low loading frequencies generally move large volumes of homogeneous soil, thus also increasing the geometric damping. In this case the structure transmits vibrations into the environment.

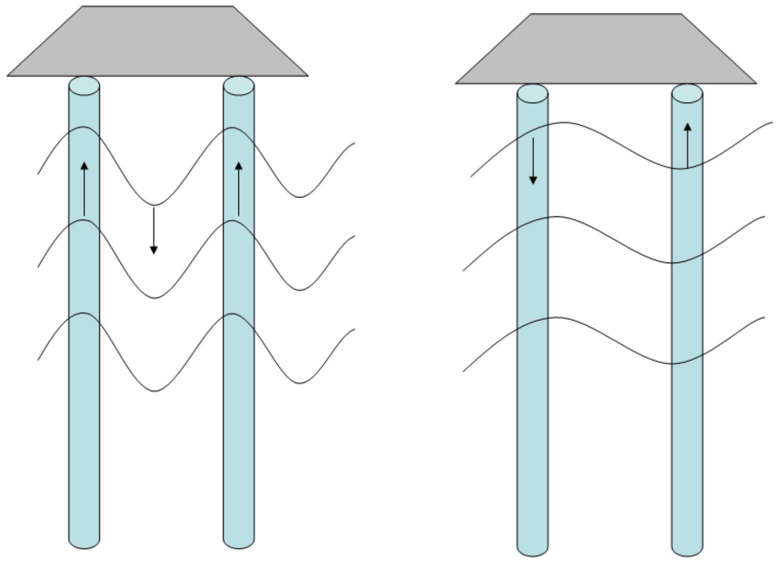

Figure 5. The impact of vibration waves on structural stiffness.

Figure 6 shows vertical displacement of the track calculated using the structure's dynamic stiffness in proportion to the dimensionless frequency a_0. Dynamic stiffness was determined based on the unit force and displacement ratio and also includes damping and inertia. The column length was L = 16 m, column spacing e = 1.5 m and shear wave velocity v_s =100 m/s. The structure's dynamic stiffness K increases significantly as the frequency increases and reaches its maximum when a_0 = 0.55. In the calculation model it was equivalent to an 18 Hz loading frequency. Stiffness was lowest when a_0 is 0.3, which was the resonance frequency.

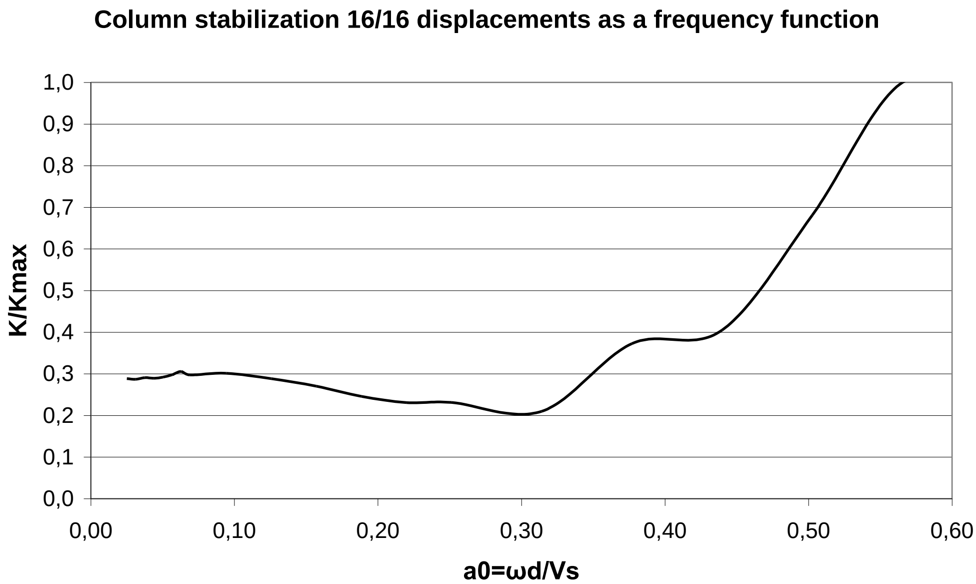

Figure 6. Column stabilization 16/16 displacements as a frequency function.

At the low frequency area (3…7 Hz, a_0 0,11…0,26), the stiffness did not depend on frequency. Wide variations were observed at higher frequencies.

Increasing column stabilization stiffness reduces vibration. Figure 7 shows calculation cases 12/12, with an impulse frequency of 5 Hz. The results in Figure 7 show that column stabilization has no real effect on environmental vibration levels, when the shear-wave velocities of columns were V_s= 200 and 300 m/s. Only when the column stiffness was V_s = 500 m/s did the displacement levels decrease, even at calculation points farther away.

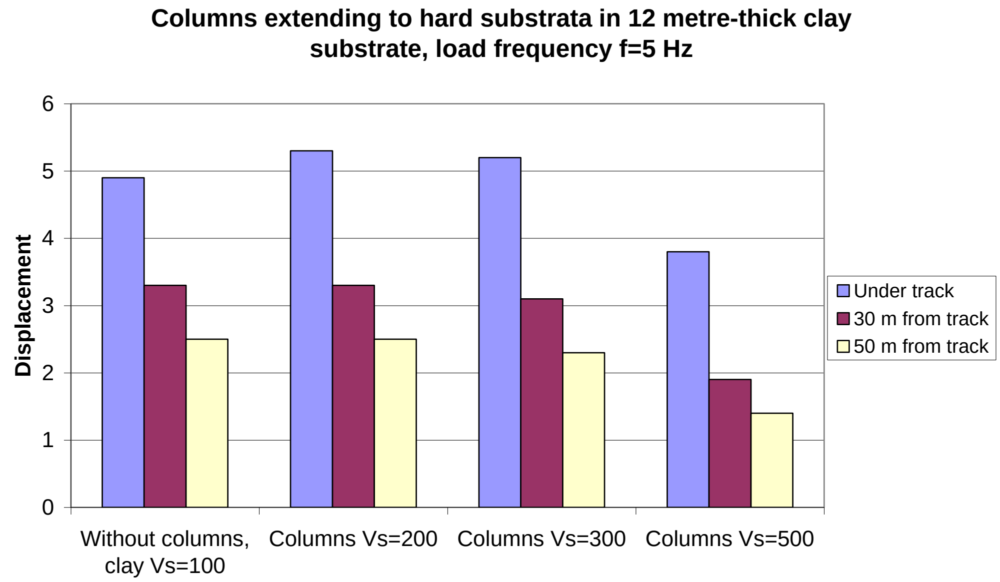

Figure 7. Columns extending to hard substrata in 12 meter-thick clay substrate.

According to calculations, column stabilization structures extending less than 12 metres to hard substrata generally reduced environmental vibrations. However, when examining the interaction of columns and soil it was discovered that column stabilized structures are sensitive to frequency variations. Figure 8 shows the displacements of an unstabilized 12 metre-thick soft soil layer and column stabilized structure extending to hard substrata at different frequencies (calculation case 12/12).

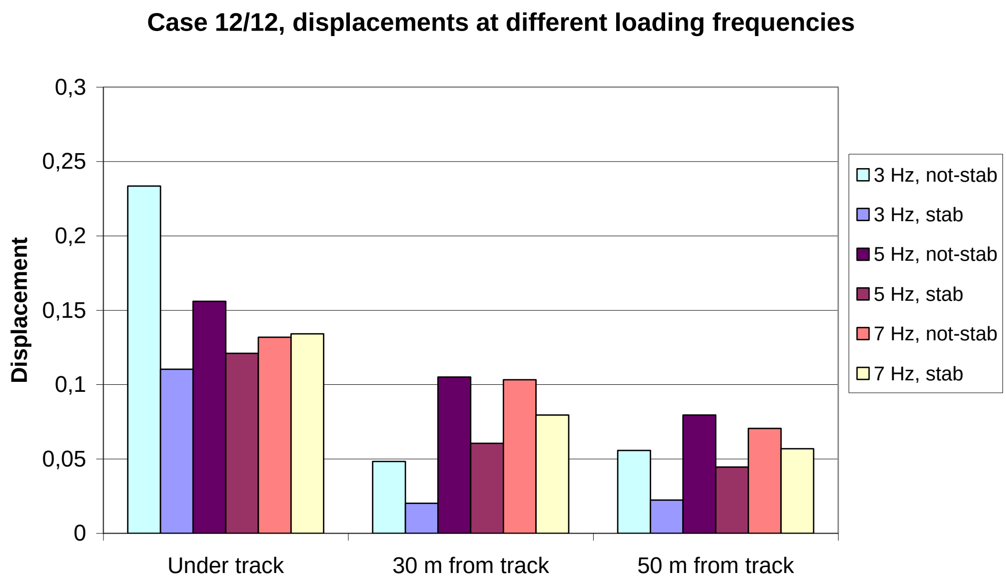

Figure 8. Column stabilization calculation case 12/12 - displacements at different loading frequencies.

When columns extend to hard substrata in a 12 metre-thick clay substrate, the columns were unable to significantly reduce vibration at a loading frequency of 7 Hz. Conversely, at a low 3 Hz frequency, the columns reduced vibration by approx. 50%. The effectiveness of column stabilization in reducing environmental vibration is clearly dependent on loading frequency. Increasing the length of columns reduces the effectiveness of stabilization.

4. Conclusions

Environmental vibrations are significantly affected by loading frequency and stabilization strength. The strength of stabilized columns is low compared to, for example, reinforced concrete piles. In a column stabilization structure the columns and soil interact together. A portion of the dynamic loading is transmitted from the columns into the surrounding clay, which reduces the amount of vibration under the track, but increases vibration in areas surrounding it. Column stabilized structures function in the same manner as what, for example, machine foundations are designed to do: they reduce the amount of vibration being exerted on the machine (track) (Hakulinen 1991). Even though track displacement levels can be reduced by stabilization, environmental vibrations cannot be predicted based on them.

In pile slab foundations pilings in soft soil strata usually transfer loads to hard substrata, which also decreases environmental vibrations.

Thus, reducing environmental vibration by improving the track substructure is ultimately a question of where the vibration is being directed: to hard substrata (pile slab structure) or the environment (stabilized structure) (Figure 9).

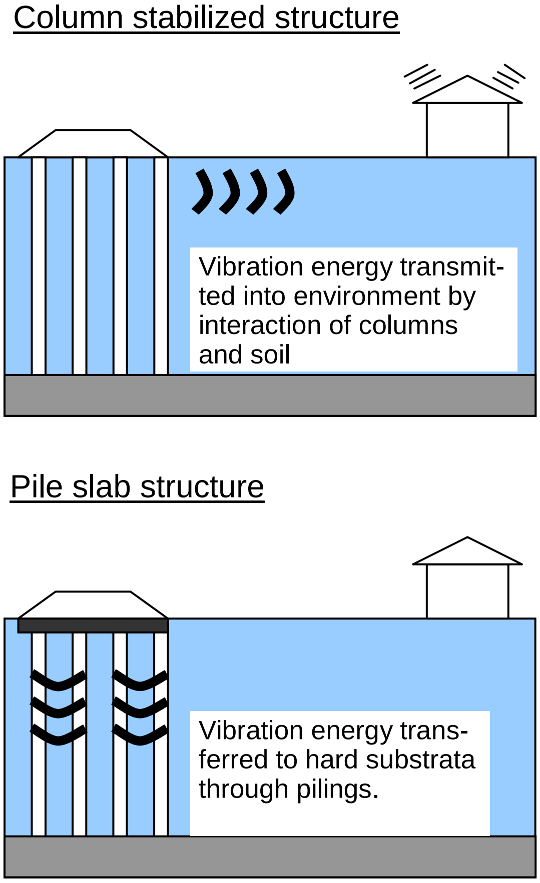

Figure 9. When soil and columns work together, they transmit vibration energy into the environment. In pile slab structures the pilings effectively transfer vibration energy downward, thus keeping environmental vibration down.

When the aim is to reduce the amount of vibration being dissipated into the environment, there are several uncertainty factors affecting the design of track substructure stabilization at this point, such as column strength, column spacing, column length and loading frequency.

In principle the calculations required during the design phase could be made using numerical methods as 3D calculations. In this case design might prove to be too time-consuming and expensive for practical construction applications and the uncertainty of the end result would affect, for example, the scope of site investigations. Dynamic analysis with numerical methods have many challenges and results must generally consider as tentative.

A more reliable basis for stabilization design would be adequately researched and simplified design methods. The development of simplified methods requires additional research and test construction. The stabilization calculations made here were 2D calculations. To ensure the reliability of results calculations should be made with 3D analyses. When conducting examinations, particular attention should be paid to stabilization strength, because strong columns appear to effectively reduce environmental vibration. The calculation results of strong columns should be compared to corresponding results for pile slab structures. It would also be good to determine how strong columns should and could actually be used and how they behave when under dynamic load. In future composite column and mass stabilization structures should be studied, particularly for use in deep soft soil strata. In this case the number of columns could perhaps be reduced, whilst also reducing the interaction of columns and soil and, in turn, the amount of vibration being transmitted into the environment.

5. Acknowledgements

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