Long-term Evenness of Pavements with Respect to Soil Deformations

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ABSTRACT: Today's requirements of comfortable and fast travelling continue to increase. Thus it is necessary to secure a long-term evenness of the pavement. The evenness is depending on the homogeneity of the subsoil. Measurements indicate that the spatial variation of soil stiffness and pavement unevenness have the same statistical characteristics. It can be posted that the evenness of the pavement is a function of the spatial variation of soil stiffness, number of vehicle passes and dynamic loads. The dynamic loads depend on the dynamic characteristic of the vehicles, their velocity and the evenness of the pavement. A simple numerical model is outlined to demonstrate this mechanism of developing unevenness with number of vehicle passes. This gives a chance to establish necessary requirements for the tolerable spatial variation of soil stiffness with respect to the raising requirements of driving comfort.

KEY WORDS: Pavement evenness, soil compaction, spectral density, soil stiffness.

1 INTRODUCTION

Soil properties vary from point to point even within nominally homogenous soil layers. Therefore it is necessary to describe the spatial variation in order to predict the geotechnical performance. E.g. differential soil stiffness leads to differential settlements, which cause an increase of dynamic forces during the passing of the vehicle. Increasing dynamic forces cause additional settlements. This process may continue until a repair of the pavement is necessary. Thus a connection for the riding comfort and requirement to the uniformity of the subsoil has to be provided.

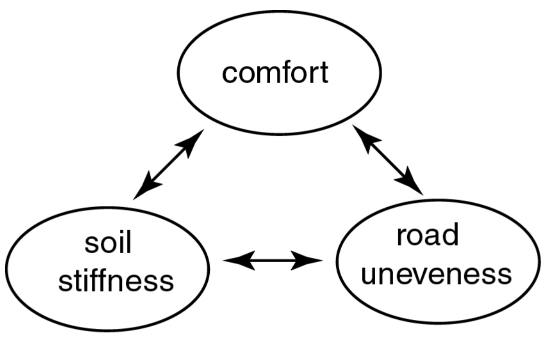

Figure1: Interaction between comfort, soil stiffness and road unevenness

The aim is to develop a simple numerical model to show that road unevenness is generated from the spatial variation of the subsoil. If this is successful, it is possible to define a tolerable variation of soil stiffness depending on the number of vehicle passes in time of use. This criteria of tolerable spatial variation of the soil stiffness is the key to secure a long term quality of traffic roads.

2 ROAD UNEVENNESS

Measurement data of road unevenness are shown in figure 2. The amplitudes of spectral road unevenness are proportional to the inverse of the angular frequencies of wave length. This characteristic is typical for an instationary statistical process called random walk. The inclination of the straight lines are –2. Therefore it is sufficient to characterise the unevenness by one point, e.g. the spectral unevenness Φ_h ($\Omega = 1$).

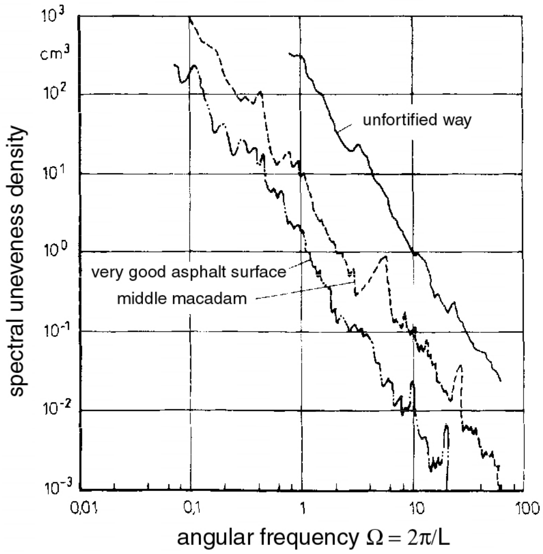

Figure2: Measured spectral unevenness density Φ_h for different road types in dependency of the angular frequency Ω (Mitschke, 1984)

From measurements it is known, that the lines are shifted to higher amplitudes with the number of passes *N*.

$$\Phi_h(\Omega = 1) = f(N). \quad (1)$$

This function also depends on the spatial variation of the initial soil stiffness and the type of dynamic load. Knowing this function it will be possible to determine the allowable spatial variation of soil stiffness after compaction, e.g. measured by the compaction meter value *cmv* (Grabe, 1992).

3 SUBSOIL

The stiffness of the subsoil can be measured continuously from the acceleration of the drum of a vibratory roller (Grabe, 1992). The so called compaction meter value (*cmv*) is shown in

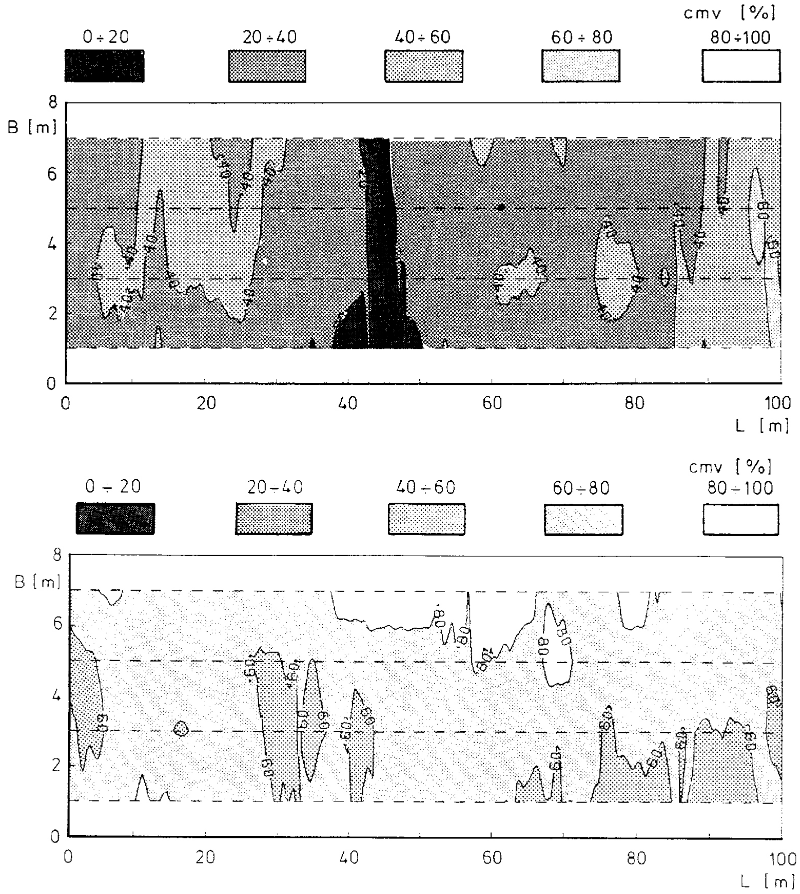

Figure3: Measured data cmv at the formation (top) and at the frost protection layer (bottom)

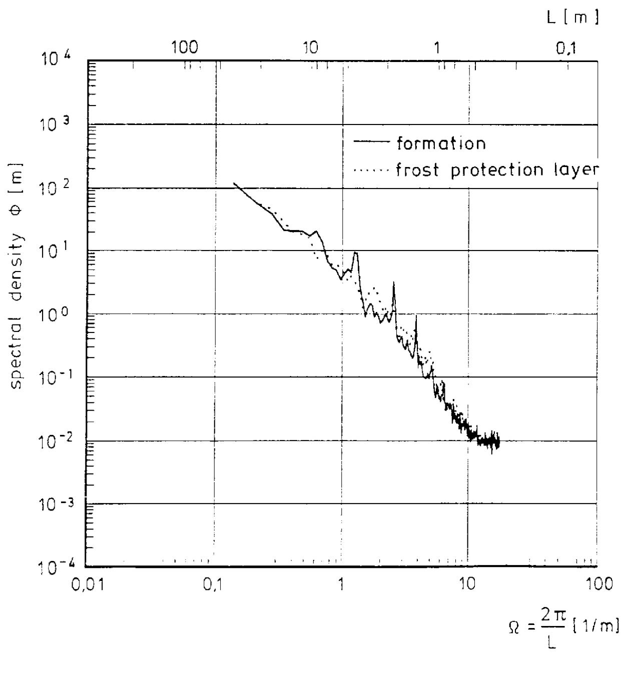

Figure4: Power spectral density Φ as a function of wave length *L* and angular frequency Ω at the formation and at the frost protection layer

figure 3. It is defined as the quotient of the acceleration amplitude measured at twice the exciter frequency and the acceleration amplitude measured at the exciter frequency. These measurements were taken on the construction of the high speed railway track between Mannheim and Stuttgart of the Deutsche Bahn AG. The measured data show that the soil stiffness of this sand and gravel varies in space. A high *cmv* indicates a relatively high stiffness and low values indicate soft soil.

The spatial variation of soil stiffness, measured as compaction meter value, shows the same characteristic like the unevenness, comparing figure 2 and 4. Therefore the following hypothesis can be drawn:

The spatial variation of soil stiffness is transferred to the road unevenness with increasing numbers of passes.

4 DRIVING COMFORT

The driving comfort of a vehicle is a function of road unevenness, driving velocity and dynamic characteristics of the vehicle. Humans do not assess the oscillation effect alone by the intensity, e.g. acceleration amplitude. They observe oscillations of same intensity for different frequency differently. Humans are most sensitive in the range of f = 4 – 8 Hz (Mitschke, 1984). Acceleration amplitudes of a_{eff} = 4 m/s^2 and a duration of 24 h affect the well-being.

5 SIMULATION MODEL

A simple numerical model is developed to investigate the stated hypothesis. First the unevenness of a young pavement and the spatial variation of the subsoil after compaction is modelled numerically. A two mass dashpot spring system is used to simulate the dynamic forces of a driving vehicle on the numerically created unevenness of a pavement. A very simple constitutive law is used to describe the soil behaviour.

5.1 Pavement (young)

The unevenness of a young pavement u_0 [mm] is created by integrating a gaussian uncorrelated variable a_i:

$$u_{0(i)} = \phi \cdot u_{0(i-1)} + a_i \qquad (2)$$

where factor ϕ = 0.99 and a_i is an uncorrelated random variable with zero mean value.

The created unevenness of the young road with a length of 1000 m is shown in figure 5 on the left. On the right the corresponding frequency spectra shows the typical 1/Ω-characteristic, compare figure 2.

5.2 Subsoil

Vibratory rollers are used to compact the soil. The depth of compaction is only some decimetres. Therefore thin layers have to be compacted to get a sufficient value of soil density. A finite element simulation of the compaction process show, that the reason for the small effect is a propagation of anelastic waves with a strong reduction of wave amplitudes

(Kelm, 2004). The calculated void ratio after one pass of a vibratory roller is shown in figure 6.

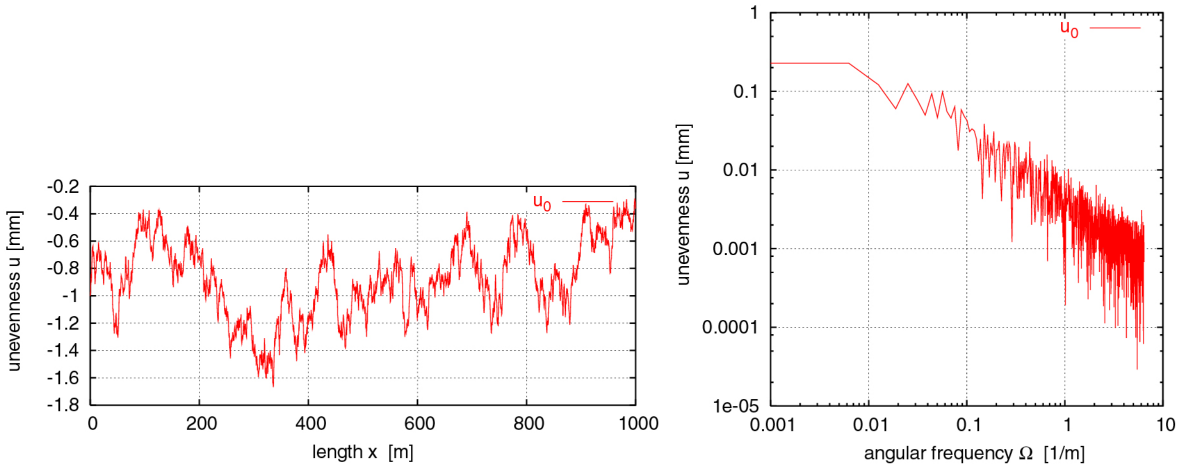

Figure5: Unevenness u of a young road (left) and unevenness u as a function of angular frequency Ω (right)

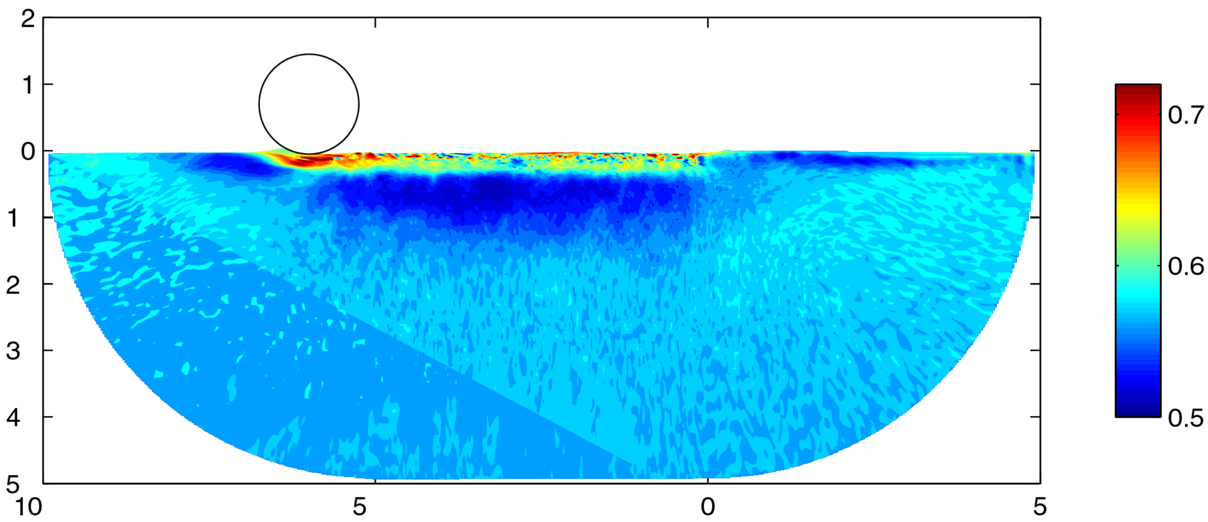

Figure6: Calculated void ratio after one pass with a vibratory roller, Kelm (2004)

A finite element simulation of million traffic passes is too time consuming and the mistake due to the integration schema would be too large. Therefore the following simple constitutive law for oedometric conditions is used:

$$u_{res} = u_0 - C_{c0} \cdot B \cdot \ln(1+N) \cdot h, \quad (3)$$

with the number of load cycles N, a factor B regarding the increasing of dynamic load due to the increasing of the unevenness. The factor B is calculated in dependency to the first dynamic load P_{dyn0}.

$$B = P_{dyn}/P_{dyn0} \quad (4)$$

The calculation of P_{dyn} is described in section 5.3.

Furthermore the influence of settlements by dynamic loads is assumed to be to the upper layer of h = 1 m. Similar strategies can be found in Triantafyllidis (2004).

The initial stiffness C_{c0} of the subsoil is numerically created like the initial unevenness of the young pavement u_0 by integrating a gaussian uncorrelated variable a_i:

$$C_{c0(i)} = \mathrm{f} \cdot C_{c0(i-1)} + a_i \tag{5}$$

Figure 7 shows the spatial variation of the stiffness coefficient and the frequency spectrum. With this simple constitutive law it is possible to calculate the settlement due to millions loading and unloading cycles for this traffic road.

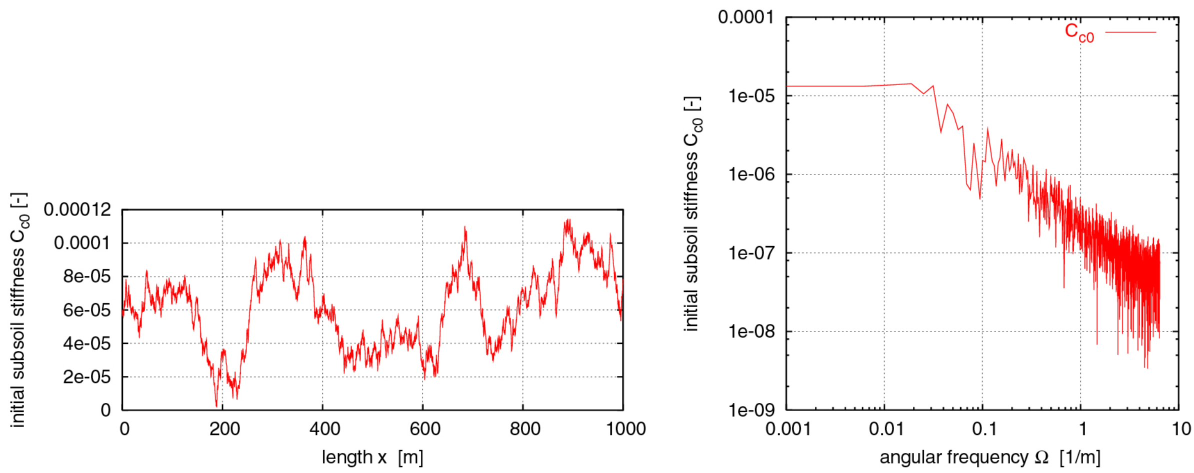

Figure7: Initial stiffness of subsoil C_{c0} (left) and initial stiffness of subsoil C_{c0} as a function of angular frequency Ω (right)

5.3 Vehicle analogous model

A two mass dashpot-spring-system is used as a mechanical model of the driving vehicle. The mass of the truck is m_1 = 3.5 t and of the wheel m_2 = 0.8 t. The spring stiffness is k_1 = 430 kN/m and k_2 = 2000 kN/m. The damping factors are c_1 = 25.5 kNs/m and c_2 = 6.4 kNs/m (Mitschke, 1984), figure 8 left.

As a first step the maximum value of the amplification function of Ω = 2.8 1/m is used to calculate the dynamic force F_{dyn} as a function of x, see figure 8 right. Thus, the dynamic forces are calculated by

$$F_{dyn}(x) = 3000 \text{ kN/m} \cdot u_{res}(x) \tag{6}$$

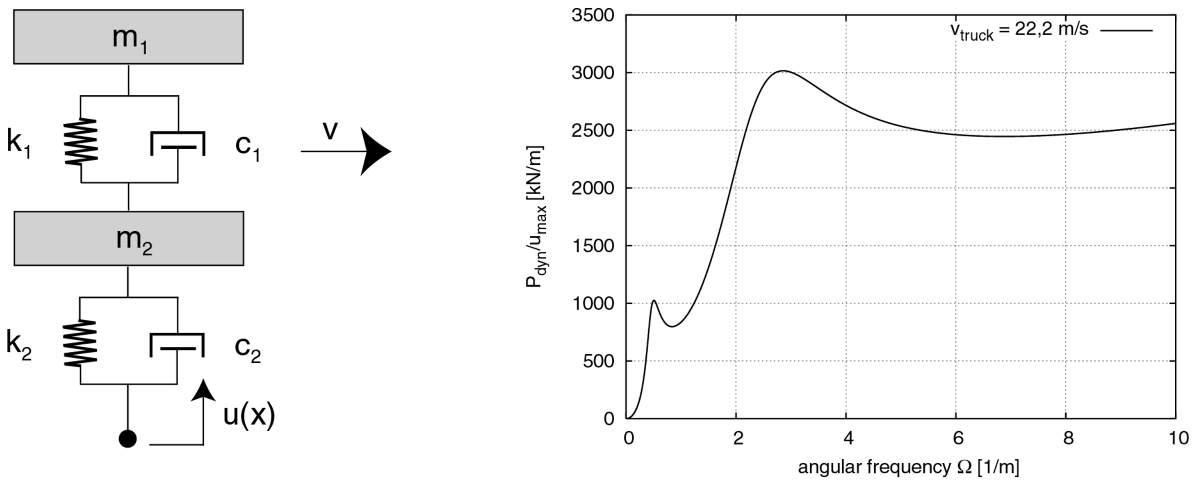

Figure8: Two mass dashpot-spring-system (left) and corresponding amplification function for a driving velocity of v = 80 km/h (right)

5.4 Results

The calculated spatial variation of the unevenness and of the soil properties given by C_{c0} with the numbers of passes are shown in figure 9. For a better comparison the results are scaled. At the beginning their spatial variation differs very much. But with several passes of vehicle the unevenness becomes similar to the soil stiffness variation. This confirms the claimed hypothesis, that the soil stiffness is transmitted to the road unevenness with the increasing of passes.

In figure 10, left, the calculated development of unevenness with number of passes looks very promising. The curves are shifted nearly parallel with increasing traffic passes. Therefore, the increasing of unevenness is depicted just for the angular frequency $\Omega = 1$ in figure 10. The unevenness of the pavement is increasing superproportional with respect to the number of traffic passes *N*.

6 CONCLUSIONS

The simple simulation model is useful to describe the process of raising unevenness of pavement due to passing vehicles. It can be concluded that the long term quality of the pavement depends essentially on the spatial variation of soil stiffness. Thus it is necessary to derive compaction criteria in space.

This will be possible if the presented model is verified by measurement data of pavements and further developed. It is planed to use a more significant constitutive model and to simulate the dynamic traffic loads in time domain.

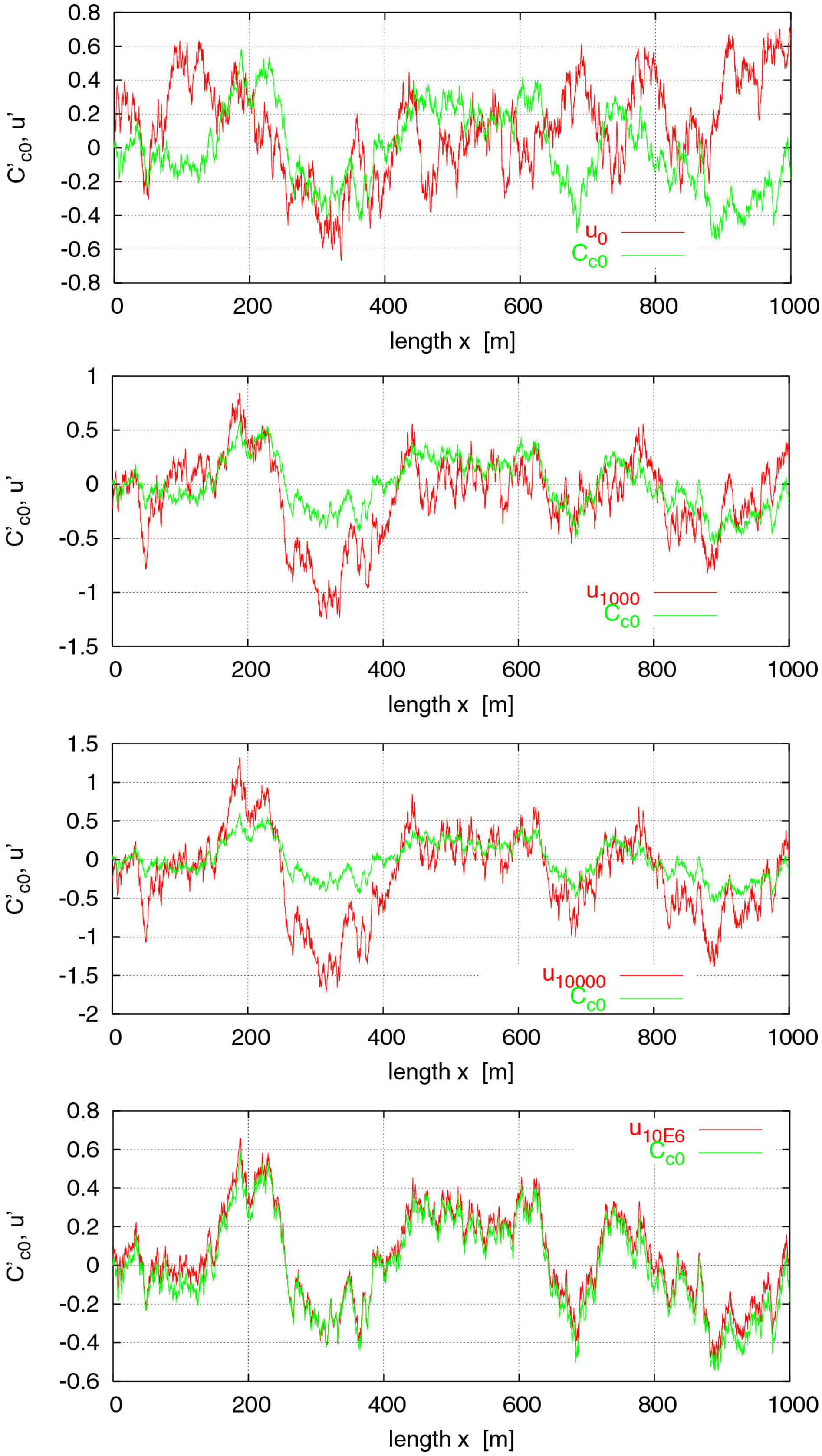

Figure9: Scaled variation of initial subsoil stiffness and scaled variation of unevenness for different load cycles

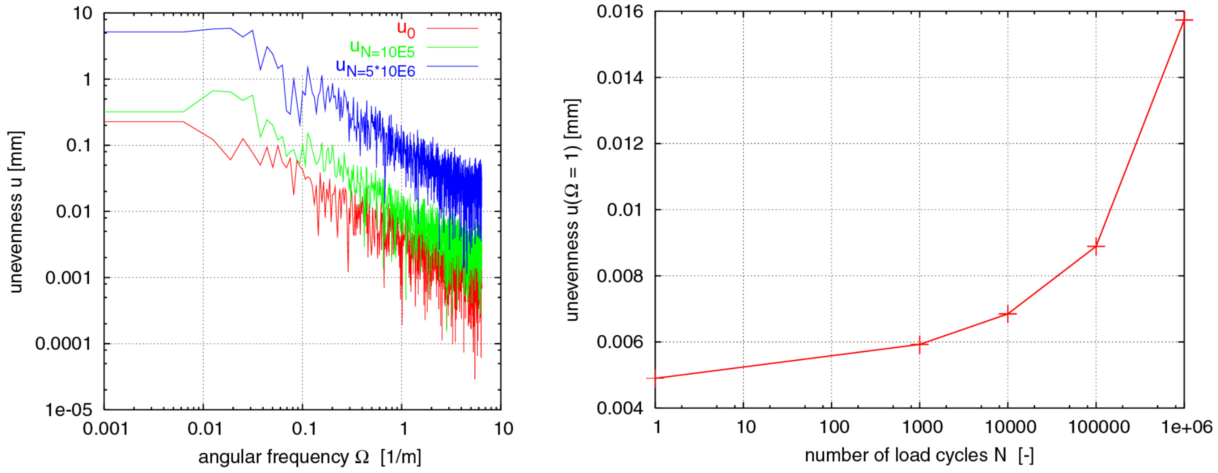

Figure10: Unevenness u as a function of angular frequency Ω for different load cycles (left) and unevenness u for the angular frequency $\Omega = 1$ as a function of load cycles (right)

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