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Resonant roller compaction of gravel in full-scale tests

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ABSTRACT

Results from a recent study indicated that compaction by vibratory roller can be made more time- and energy-efficient by operating at a vibration frequency close to resonance. In this paper, the results are verified and the reduction in operating time is quantified by conducting detailed full-scale tests under realistic conditions at two frequencies: the standard operating frequency of the roller and a lower frequency slightly above resonance. Compaction was done in two tests per frequency with 16 passes in each test. The obtained compaction was quantified using a combination of measurement techniques, including laser levelling, nuclear density gauge and static plate load tests. The results confirm that the lower frequency is more efficient for compaction and that utilizing resonance in the roller-soil system can reduce the number of passes. In addition, lowering the frequency reduces energy consumption, environmental impact and machine wear.

Introduction

Soil compaction is obtained by relative motion of the soil particles and the most important parameter for densification is thus the strain amplitude [5,20] along with the number of loading cycles. A vibratory roller generates vibrations by means of a rotating eccentric mass in the drum, which gives rise to dynamic loads in the soil. This causes a cyclic shear strain with an amplitude depending on the vibration amplitude. It is thus essential to maintain a high amplitude in the soil during compaction. Recently, it has been shown that operating close to the coupled resonant frequency of the roller-soil system can increase the vibration amplitude and the compaction efficiency [18]. Since rollers operate above resonance, this implies lowering the frequency to a value that is closer to resonance. A lower frequency is also beneficial from the point of view of energy and fuel consumption, environmental impact and machine wear.

Utilization of resonance for increased compaction efficiency was discussed in early studies [6–9]. None of these studies included experimental results from variable-frequency roller compaction. In deep compaction using vibratory probes, however, the concept of resonant compaction has been applied in a number of projects with successful results [11,12]. Automatic frequency control of vibratory rollers has been discussed by [3,4,19] and the technology for automatic frequency adjustment is already available for asphalt compaction rollers [21].

To investigate whether resonance can be utilized to obtain a more efficient compaction process, the influence of frequency on vibratory surface compaction of granular material was studied experimentally in a recent paper [18]. The results suggested that compaction can be made more time- and energy-efficient by lowering the vibration frequency of the roller to a value closer to resonance. The tests were conducted for nine different frequencies in six passes on previously compacted material with measurements of settlement and density. The study was based on small-scale tests in the laboratory with a vibrating plate [17] and showed that the frequency-dependent compaction behaviour is similar for both a roller and a plate.

This paper verifies the results of the previous study statistically for the same roller and test material by conducting more extensive tests under realistic conditions with an extended amount of measurement techniques. Furthermore, it quantifies the possible reduction in operating time that results from a lower compaction frequency. Detailed tests were conducted at two selected frequencies where the number of passes was increased to 16, the material was previously un-compacted and static plate load tests (SPL) were added to the measurements.

Abbreviations: COV, Coefficient of variation; NDG, Nuclear density gauge; PDF, Probability density function; SPL, Static plate load test.

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Methods and materials

The tests were conducted with a Dynapac CA3500D single-drum soil compaction roller at Dynapac's indoor research facility in Sweden. The roller was operated at the high amplitude setting, with an eccentric moment of 7.38 kgm and a nominal amplitude of 1.9 mm. The actual displacement amplitude, however, depends on the dynamic response of the soil, as presented in [18]. The resulting amplitude is amplified around resonance and is increasing for each pass due to increasing soil stiffness. The roller and test bed are shown in Fig. 1. The test surface had a length of 20 m and a width equal to that of the roller's drum, 2.13 m. The test material was well-graded gravel (GW), consisting of crushed rock with coefficient of uniformity $C_u = 60$, coefficient of curvature $C_c = 3$ and specific gravity $G_s = 2.696$. The maximum density, determined by modified Proctor test, was 2230 kg/m^3. The roller had a standard operating frequency of 31 Hz but modification of the equipment facilitated a variable frequency setting. Tests were conducted at two frequencies – the standard operating frequency of the roller, 31 Hz, and 20 Hz, which is slightly above the coupled resonant frequency. The resonant frequency was 17 Hz, determined in the previous study. Both tests were repeated, resulting in 2 test cycles per frequency, i.e. 4 in total. In each test, the material was loosened down to 60 cm using an excavator, followed by one preparatory static pass of the roller and 16 vibrated passes, with intermediate measurements. The base below the gravel layer that was loosened consisted of 0.5 m of the same material and then a rock fill layer. The properties of the rock fill are unknown but the material can be assumed to be very well-compacted considering that compaction tests have been conducted at the same location for more than 30 years.

The relative compaction between the two frequencies was quantified using three different measurement techniques. All measurements were conducted after 2, 4, 8, 12 and 16 passes. As in the previous study, settlement was measured by laser levelling and density was estimated by means of a horizontal nuclear density gauge (NDG) that measured nuclear decay between a transmitter and three adjacent boreholes. SPL tests were also conducted. Settlements were measured at 30 points spread evenly across the surface (10 longitudinally along the surface and 3 transversally along the width of the drum). NDG tests were conducted in 3 locations with measurements from 40 mm to 500 mm depth at an interval of 20 mm. The water content was measured at each NDG measurement location from 0 to 500 mm depth. During all tests the average water content was 3.3% with a coefficient of variation, COV, of 3% while the maximum and optimum water content was approximately 6%. Since the material is free-draining, it is not particularly sensitive to variations in water content. As in the previous tests, however, it was considered more important to have a constant water content than to be close to the optimum, based on previous results. The soil was covered with plastic between each pass to minimize evaporation and the samples obtained after each cycle, 5 days apart, showed no variation in water content, which was also confirmed by intermediate samples during the tests. The SPL tests were performed in 4 locations with a 300 mm diameter plate using the roller as the loading device [15]. In the SPL tests, the deformation versus deflection is measured in 2 loading cycles, where the deformation modulus of the second cycle, E_{v2}, represents the stiffness of the subgrade and the ratio between the moduli in the second and first cycles, E_{v2}/E_{v1}, is considered a measure of the degree of compaction. The roller, material properties and measurement techniques (excluding SPL tests) have been described in more detail in [18]. Table 1 summarizes the number of tests conducted at each frequency and pass.

Results and discussion

The settlements after 2, 4, 8, 12 and 16 passes are shown as probability density functions (PDFs) in Fig. 2 for the two test frequencies. Each PDF is based on 60 settlement measurements (Table 1) with the respective variation in the sample. The variability with respect to the COV of the sample is overall low, but decreases significantly from 5.5% for 31 Hz to 3.8% for 20 Hz (Table 2). The variability is also relatively constant over the range

Fig. 1. Test bed and roller in operation.

Table 1
Number of measurements after 2, 4, 8, 12 and 16 passes at each frequency.

Test	Cycles	Points/pass	Measurements/point	Measurements/pass
Levelling	2	30	1	60
NDG	2	3	72	432
SPL	2	4	1	8
Water content	2	3	5	30 (after 16 passes only)

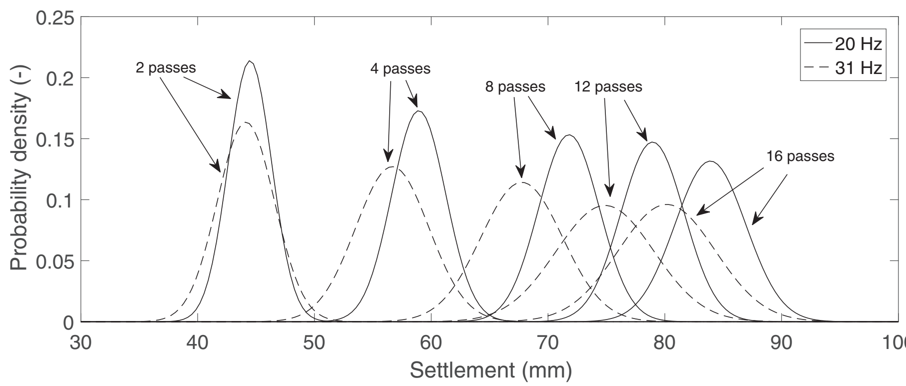

Fig. 2. Probability density functions of settlement for 20 Hz and 31 Hz.

Table 2
Summary of test results; number of tests conducted (n); logarithmic regression models, coefficient of correlation (R^2); and coefficient of variation (COV) with respect to the logarithmic regression models.

Parameter	Frequency, f	Number of tests, n	Regression: settlement, s and elastic modulus, E	Coefficient of correlation, R^2	Coefficient of variation (COV)
Settlement s	20 Hz	300	$s = 19\ln(n) + 32$ mm	0.97	3.8%
	31 Hz	300	$s = 17\ln(n) + 32$ mm	0.93	5.5%
Deformation modulus of the second cycle-E_{v2}	20 Hz	40	$E_{v2} = 29\ln(n) + 36$ MPa	0.97	4.3%
	31 Hz	40	$E_{v2} = 23\ln(n) + 43$ MPa	0.83	9.6%
Deformation modulus ratio E_{v2}/E_{v1}	20 Hz	40	$\frac{E_{v2}}{E_{v1}} = -0.93\ln(n) + 5.4$	0.87	7.1%
	31 Hz	40	$\frac{E_{v2}}{E_{v1}} = -0.53\ln(n) + 5.2$	0.36	12.5%

of the number of passes. A statistical t-test to compare the slopes of the regression lines shows that there is significant difference at >99% level of confidence in the slopes for these two compaction frequencies.

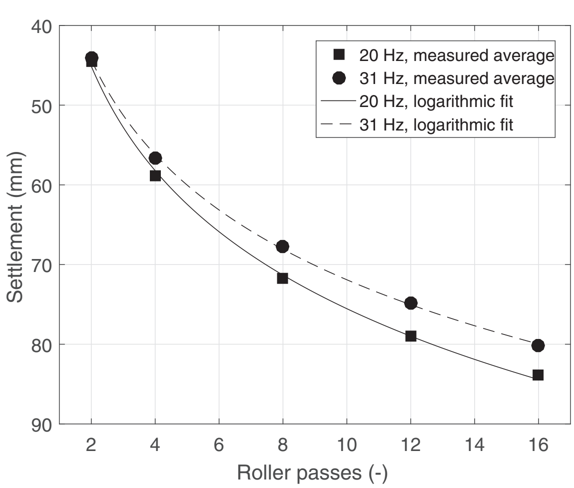

Fig. 3. Average settlement.

Fig. 3 shows the average settlement with fitted logarithmic functions (Table 2). The settlement measurements suggest that the number of passes can be reduced by approximately 20% by lowering the frequency from 31 Hz to 20 Hz. Although settlement is a good indicator of the compaction of the soil, as established by [16], it is not directly correlated to any acceptance criteria, such as density or stiffness.

Wersäll et al. [18] used measurement by NDG to estimate depth-dependent density variation before and after compaction. However, due to the uncertainty in density measurements, the settlement was considered a more reliable measure of compaction. The limitation of NDG is partly due to the uncertainty in transforming nuclear decay to density, resulting in a large variation. Furthermore, the variation in density that is estimated is very small, whereas settlement or stiffness varies to a larger extent, which was discussed in the previous paper. Fig. 4 shows the average estimated density after 2 and 16 passes, where each curve is based on 432 measurements (Table 1) and intermediate passes are omitted. The small difference in density illustrates the difficulty in detecting variations between frequencies. The difference between 20 Hz and 31 Hz is not in perfect agreement with the previous study, which can be explained by the similarity in estimated density between the two frequencies in relation to the uncertainties discussed above.

Fig. 5 shows the average, upper and lower limit and logarithmic fit of E_{v2}, i.e. subgrade stiffness determined by SPL (Table 2). The

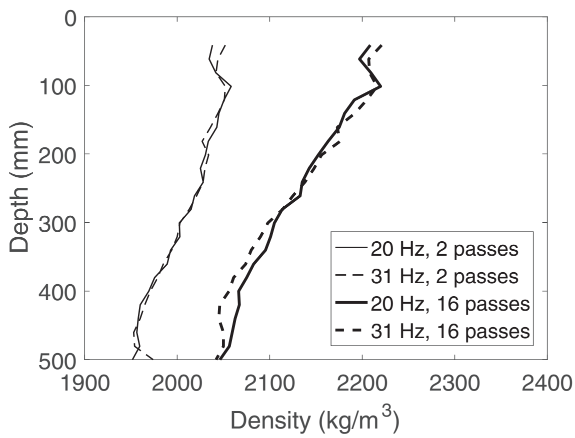

Fig. 4. Average density estimated by NDG after 2 and 16 passes.

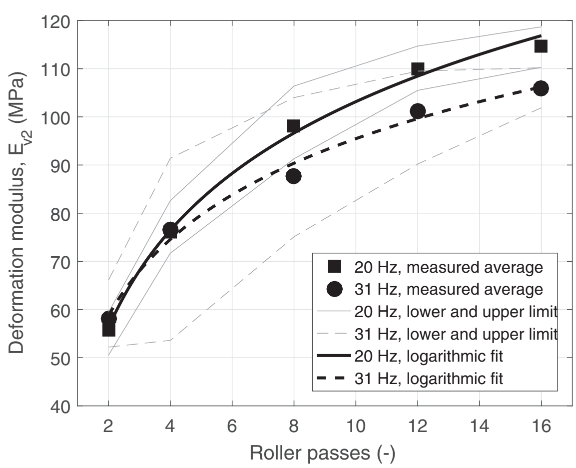

Fig. 5. Deformation modulus E_{v2} from static plate load test.

values for each frequency and pass are based on 8 measurements (Table 1), which means that the logarithmic fit of E_{v2} is based on 40 measurements for each frequency. A higher value of E_{v2} indicates that the soil stiffness is greater and thus that the compaction effort has been more effective. If using the logarithmic fit curves, the same stiffness is achieved in 11 passes at 20 Hz as in 16 passes at 31 Hz (Table 2), implying a reduction in the required number of passes of approximately 30%. However, the variation in test data is large compared to the settlement test, as can be seen in the limits for minimum and maximum values. This is expected since the variability with respect to point-to-point measurements of elastic modulus is relatively large, see e.g. [2]. The evaluated COV, however, is of the same order of magnitude as, or lower than, previously published data on evaluated soil elastic modulus from different methods [1,10,13,14] for compacted soil with roughly the same magnitude of soil elastic modulus (60–120 MPa). This indicates that the tests have been performed under controlled conditions with a sufficient number of tests. The evaluated COV of the sample decreases from 9.6% for compaction at 31 Hz to 4.3% for compaction at 20 Hz. Furthermore, a statistical t-test to compare the slopes of the regression lines shows that there is significant difference at >99% level of confidence in the slopes for these two compaction frequencies.

Fig. 6 shows E_{v2}/E_{v1} for the same tests. The ratio is often regarded as a measure of the remaining compaction potential in the subgrade where a lower ratio indicates that there is less compaction potential left in the subgrade, i.e. that a larger portion of

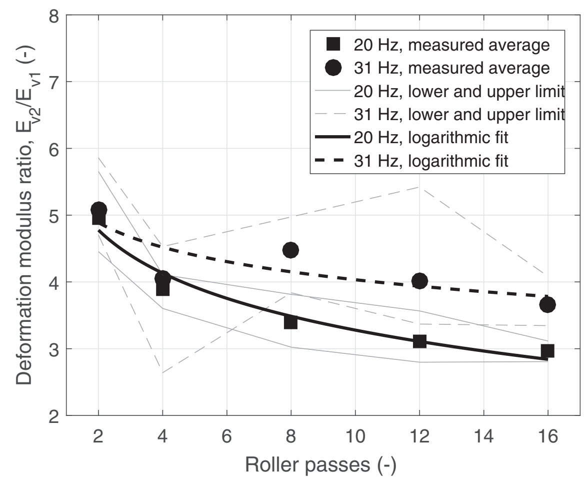

Fig. 6. Deformation modulus ratio E_{v2}/E_{v1} from SPL tests.

the possible compaction has taken place. However, this interpretation is debated. Since E_{v1} not only represents the subgrade stiffness but also the initialization of contact between the plate and the soil, the ratio is affected by the initial conditions before full contact is obtained and can thus be misleading. Especially if the soil is well-compacted, other factors will influence E_{v1}. The ratio is presented here for the sake of completeness but should be interpreted with caution. Assuming that the ratio represents remaining compaction potential, the results are significantly better for 20 Hz than for 31 Hz but the variation and uncertainty in the test results are significant. Especially after four passes, the ratio for 20 Hz deviates significantly from the general trend, which could be related to variations in initial conditions, as discussed above. After 16 passes, however, the variation is quite small. The evaluated COV of the whole sample, with respect to the logarithmic curve fitting, decreases from 12.5% for compaction at 31 Hz to 7.1% for compaction at 20 Hz. A statistical t-test to compare the slopes of the regression lines shows that the slopes of the regressions are significantly different at a >99% level of confidence.

Taking all measurements into account, it is evident that compaction under the conditions presented in this paper is more effective at a vibration frequency of 20 Hz than at the standard operating frequency of 31 Hz. By interpreting settlements and results from plate load tests, a reduction in the number of passes of between 20% and 30% seems possible. The results confirm the conclusion from Wersäll et al. [18] that it is more efficient to operate at a frequency slightly above resonance. However, the findings cannot be directly applied to other materials or rollers but it is reasonable to assume that resonance can be utilized for other rollers and granular materials. Lowering the frequency also significantly reduces energy consumption, environmental impact and machine wear. The implications of a lower operating frequency and the applicability of the results to other conditions have been discussed in more detail in the previous paper.

Conclusions

Four full-scale compaction tests were conducted using a vibratory soil compaction roller at two frequencies. The following conclusions can be drawn:

- The tests verify the previous results that operating at a frequency close to resonance can increase the compaction efficiency.

- Settlement of the subgrade, which is considered the most reliable measure of compaction, indicates that the number of passes can be reduced by approximately 20% by lowering the frequency from 31 Hz to 20 Hz.
- SPL tests, which are directly correlated to stiffness-based acceptance criteria, show an even greater improvement but with higher variability.
- Density measurement by means of NDG has too high variability in relation to the density variation to draw any definite conclusions.
- It is recommended that crushed rock is compacted at a lower frequency that is close to the resonant frequency, which seems beneficial in terms of reducing operating time, fuel consumption, environmental impact and machine wear.

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