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An Evaluation of Vibratory Plate Compactors

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SUMMARY A study has been undertaken to obtain quantitative data on the energy outputs from vibratory plate compactors. Data have been obtained for four compactors of various sizes operating on a thick layer of Perth sand of medium density. It has been shown that the peak particle velocity measured near the surface is highly dependent upon the operating frequency of the machine and decays approximately in proportion to the inverse of the distance from the source. The transmitted vibration has been compared in terms of human and structural response with limits found in the literature.

1. INTRODUCTION

The Vibratory Flat Plate Compactor has become a very common and effective means of soil densification for residential construction in Perth. These units are especially suited to cohesionless soils such as sand and gravel which respond well to compaction produced by a combination of pressure and vibration . Tynan (1973), in what was essentially an Australian State of the Art report wrote: "A large amount of information is available on the subject of vibration in civil engineering. Much of it concerns the effects of machine vibration, earthquakes, and quarrying and blasting activities on buildings and foundations. By comparison there is only a small amount of literature on the damaging effects of vibrations generated by construction activity". This still appears to be a true statement. What is of interest however, is that nearly all information on soil compactors relates to vibrating drum rollers and plate compactors are only referred to in passing. It was the lack of quantitative data on vibratory plate compactors that prompted the research programme reported in this paper.

Vibratory plate compactors deliver impact blows to the ground surface through the action of a pair of counter rotating eccentric weights driven by the power pack of the machine. In this way the centrifugal forces resulting from the rotating masses are combined in the vertical direction and annulled in the lateral. The repeated beating of the compactor plate onto the ground surface, results in the creation of ground borne vibrations. The energy wave propagates through the soil behind a hemispherical front with its magnitude and manner of transmission being dependent upon the characteristics of the vibrating source and also upon the nature of the soil medium.

The dissipation of ground vibrations is affected by the geometric configuration of the wave front and the damping ability of the soil. Forssblad (1973) considered that wave propagation and damping do not vary to any large extent between different types of soils, and that the geometric damping is responsible for a large proportion of the decrease in amplitude as the distance from the source of energy increases.

1.1 Wave Forms

Energy transmissions through an elastic body such as soil takes place in three distinct wave forms

- Compression waves (P,longitudinal or dilation waves).
- Shear waves (S, transverse or distortional waves).
- Surface waves (Love or Raleigh waves)

Tynan (1973) reported that it has been determined that the transmission of the total wave energy was divided as follows:-

Compression waves	26%
Shear waves	7%
Raleigh waves	67%

Compression and Shear waves travel through the medium behind a hemispherical front moving radially out from the source in all directions. As such they are collectively called body waves and together total 33% of the total input energy.

Surface waves radiate out from the source parallel to the ground surface and to a depth of about one wave length below it. These surface waves contain 67% of the total input energy.

Compression waves maintain the highest velocity of the three types. Propagation is by means of longitudinal compression and rarification of the media, similar to the transmission of sound in air.

Shear wave propagation occurs at a velocity lower than the compression wave and involves only the distortion of the media particles without change in their volume. The shear wave particles move at right angles to the direction of propagation.

In the case where a free surface exists, surface waves may form. These waves occur either as Raleigh waves in which the particles move in elliptical paths, or Love waves which are characterised by the horizontal particle movements at right angles to the direction of propagation. Interference patterns between Love and Raleigh waves often result in complex wave forms. The propagation velocity of surface waves is well below that of body waves.

Tynan (1973) reporting earlier work by Millar and Pursey suggested that body waves decay in proportion to the square of the distance from the source while the surface waves decayed in proportion to the square root of this distance. Hence because of the greater energy involved, the smaller dissipation rates and the two-dimensional surface propagating nature of the surface wave, this wave type is the most significant in its effect on humans and surface structures.

1.2 Damage Criteria

The effect of vibrations on a structure is greatly affected by the duration of the vibrations. Transient vibrations such as induced by earthquakes or blasting can have a very much higher peak value than those induced by steady state vibrations without causing damage because of the build up of resonant vibrations with time.

Most authorities now agree that peak particle velocity is the main criterion to be considered in the study of damage from ground vibrations, while human response is generally defined in terms of single plane (vertical) motion (Forssblad (1973), Siskind et al (1980), Tynan (1973), Wiss (1981)). The highest peak particle velocities permissible according to various codes and literature sources for buildings with foundations on soil vary between 2 and 50 mm/sec. The Australian Standard Earthquake Code AS 2121-1979 relates MM VI to a peak particle velocity of 50 mm/sec representing the particle velocity below which no damage to structures should occur. This limit of 50 mm/sec is commonly presented as the threshold of damage for blasting and other construction activities in a number of sources quoted by Siskind et al, Tynan and Wiss.

Some authors suggest that this 50 mm/sec velocity should be limited to short duration vibrations such as from blasting or earthquakes and that a lower limit should be used for longer duration vibrations such as from soil compaction. All of the references above include reference to a limiting peak particle velocity of 10 mm/sec below which damage would not normally be expected from long duration vibrations in houses of normal standard. On the other hand, Tynan also refers to a proposed German Code (DIN 4150) and his Table II from that draft code is reproduced as Figure 1.

TABLE II

VIBRATION LIMITS PROPOSED BY DIN 4150
(8-80 Hz)

Class of Building	Type of Building	Max Velocity $(v_m)^*$ mm/s
I	Historical and ancient buildings, ruins and monuments	2
II	Buildings visibly damaged, cracked	4
III	Structurally sound buildings (technically in good order)	8
IV	Industrial buildings, concrete buildings — generally without plaster	10-40

$^*v_m = \sqrt{v^2_{xm} + v^2_{ym} + v^2_{zm}}$

Figure 1 Vibration Limits (Tynan 1973)

The DIN 4150 code suggests that buildings already visibly damaged and cracked should not be further damaged by vibrations with peak velocities less than 4 mm/sec. This appears to be the strictest criteria suggested anywhere in the literature and is lower than another limit of 5 mm/sec quoted by Tynan below which it is suggested there should be no "architectural" damage and that complaints due to human response should be reduced. The DIN 4150 Class I relating to historical and ancient Buildings, ruins and monuments, with a maximum particle velocity of 2 mm/sec does not appear to be relevant to conditions in Perth generally.

1.3 Human Response

Tynan wrote: "human reaction to vibration .... is relevant since most claims for damage by ground vibrations are dependent upon the sensitivity of people to vibrations, their concern for the possibility of damage to property occurring and their reaction when interpreting damage". His Figure 8 reproduced here as Figure 2 indicates that ground vibration becomes perceptible to most people at a level which is less than one-tenth of the magnitude of the DIN 4150 Class II limit.

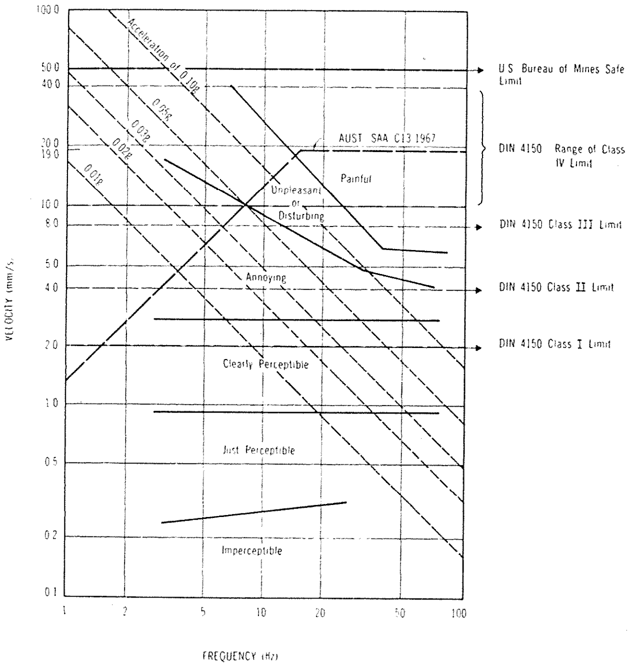

Fig. 8 Human sensitivity to vibrations showing German. US and Australian limits considered safe for buildings. Human reactions listed are to vertical vibrations (after Reiher and Meister 1931 with the addition of other standards applying to resultant velocities).

Figure 2 Vibration Limits (Tynan 9173)

2. FIELD TESTING PROGRAMME.

The programme of testing was undertaken primarily to determine the relationship of peak particle velocity with distance from the source for a number of types and sizes of vibratory flat plate compactors. Measurements were also made of the energy outputs directly from the plates as a function of operating frequency. In addition an assessment of the frequency response of the soil was made with the CM 13 compactor.

The testing was undertaken on a body of sand approximately 30 m deep overlying limestone. SPT testing produced values averaging around 8 between 0 and 4 metres deep and values averaging around 35 were obtained between 4 and 30 metres depth. The SPT testing did not permit determination of the groundwater level but it was anticipated to be no greater than 5 metres below the surface.

Four vibratory compactors were used. They were chosen because they were readily available locally through machinery hire firms and they covered a range of sizes from relatively small to the largest in general use. The details of each is presented in Table 1.

	DYNAPAC CM 13	VIBROMAX ATN 1000	WACKER DVU 4001	VIBROMAX ATS 6002
Speed	25 m/min	15 m/min	27.5 m/min	23 m/min
Compaction Depth	30 cm	40 cm	100 cm	75 cm
Vibration frequency	75 Hz	28 Hz	35 Hz	30.5 Hz
Weight	145 kg	300 kg	554 kg	870 kg
Rated power	4.6 kW	3.7 kW	6.62 kW	8.1 kW
Centrifugal Force		13 kN	40 kN	60 kN

Table I Vibratory Plate Compactor Details

Ground vibrations were measured by means of a triaxial cluster of Bruell and Kjaer 4339 Accelerometers mounted onto a 400 millimetre long steel sensor peg. The peg was driven vertically such that only 50 millimetres protruded above the ground surface. The individual compactor being tested was then run for a period of approximately 1 minute at varying distances from the sensor peg. The peg was oriented such that the vibration measurements taken could be considered as longitudinal, vertical and transverse to the line of action of the compactor.

The accelerometer outputs were amplified and loaded onto magnetic tape in the field for later playback and analysis in the laboratory. Each compactor was tested on a separate strip in order that the soil densification from previous tests did not influence any subsequent results. For the same reason, tests on each compactor began at the furthest marker and came progressively closer to the recording peg.

In order to evaluate the output from each compactor an accelerometer was mounted directly on to the compactor plate by means of a pretapped hole and stud. The transducer ouput was amplified and integrated by use of a charge amplifier before loading onto magnetic tape. In this way the recorded signals were those of the plate velocity and at a suitable level for further analysis.

The frequency response of the soil was determined at the same site as for the previous tests. The CM 13 compactor was used as the energy source because of its high operating frequency and the ability to cover a large frequency range by altering the speed of the engine.

One accelerometer was attached to the compactor plate and a second accelerometer was placed on the sensor peg to monitor the vertical ground vibrations. With this setup it was possible for the vertical outputs of the plate and of the ground vibration to be recorded simultaneously. The actual test was performed by running the compactor at a distance of 3 metres from the sensor peg and varying the speed of the machine from idle to full speed so that a comprehensive frequency band width could be obtained.

3. ANALYSIS

At any particular surface location there is vibration in all three orthogonal directions due to the mixing of the body and surface transmitted waves. Added to that are vibrations reflected or refracted from strata below the surface.

The plate compactors generate a strong harmonic and half harmonic spectrum of energy into the soil. The resulting complex wave forms recorded on each transducer during the tests were analysed using a spectral analyser into discrete frequency modes by means of a fast Fourier transform function. The accelerometer data gathered from the field was integrated prior to admission into the spectral analyser in order to obtain the particle velocity characteristics. An example of the spectral data obtained is presented on Figure 3.

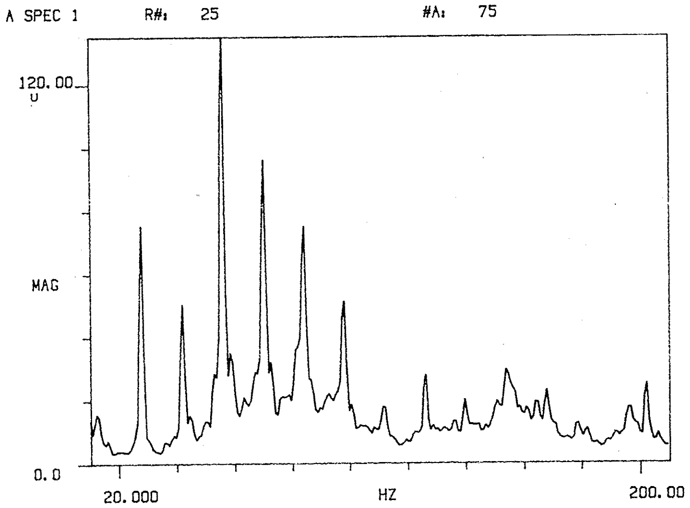

Figure 3 Spectral Data. ATN 1000

Figure 3 presents the longitudinal vibration 15 metres from the ATN 1000 compactor. The vertical axis presents the magnitude of the particle velocity in terms of micro metres per second. Thus the maximum particle velocity presented on Figure 3 is of the order of 0.13 mm/sec at a frequency of approximately 56 Hz (or twice the operating frequency of the machine). The six pronounced spikes represent the velocities at each half harmonic from 1 to 3.5 times the operating frequency. This plot represents the form of the data obtained from all transducers, although closer to the compactor the peaks in velocity extended to a frequency of 5 harmonics or more in some the the data.

For any data sample then, the overall particle velocity of the spectrum is determined as the root mean values of the squares of the maximum velocities of each successive peak, i.e.:-

$$V_{mx} = (V_{1x}^{2} + V_{2x}^{2} + V_{3x}^{2} + \ldots\ldots)^{1/2} \quad (1)$$

Where V_{1x} = Maximum Velocity of the first peak

V_{2x} = the second peak

V_{3x} = Maximum Velocity of the third peak

etc

and x = the vibrational direction (i.e:- transverse, longitudinal or vertical).

Further, the peak particle velocity for any one location is determined as the vector sum of the longitudinal, vertical and transverse components i.e.:-

$$V_t = \left(V_{mx}^2 + V_{my}^2 + V_{mz}^2\right)^{1/2} \qquad (2)$$

where V_{mx}, V_{my} and V_{mz} are the maximum measured particle velocities in the three mutually perpendicular directions. It should be noted that since these three components will be unlikely to have maximum values at the same instant, the peak particle velocity (V_t) as determined above is likely to be a conservative value.

The final stage in the analysis of the data relating peak particle velocity to distance from the source for each compactor involved a least squares fit of the data. Figure 4 presents the data for all four machines presented in both graphical form and the least squares equation format.

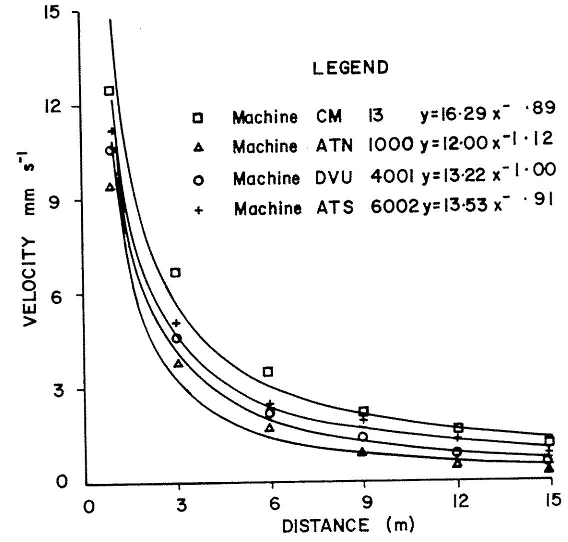

Figure 4 Peak Particle Velocity with Distance from Source

Analysis of the data obtained from the accelerometer mounted on the compactor plate was accomplished using the same methods as in the ground borne vibrations above. A peak velocity versus frequency relationship was obtained using the spectral analyser and the overall vertical particle velocity and energy of the spectrum derived as before.

Transfer function theory has been used within this study to observe the frequency response of a soil body subjected to an excitation. The spectral analyser was used to display and correlate the waveforms of the input from the compactor plate and response from the sensor peg. The ratio of the response of the soil (in terms of velocity) to the excitation of the plate (in terms of acceleration) is defined as the transfer function. Depending upon the nature of the system the transfer function will vary with the frequency of the excitation force, reaching a maximum at the point of resonance of the system as a whole.

The coherence function gives a measure of the correlation between two random signals in the frequency domain. If the coherence is equal to zero at a particular frequency the two signals are said to be incoherent and uncorrelated. If it is equal to one the signals are said to be coherent and well correlated.

Figure 5 presents both the transfer and coherence functions for the soil at the site under test for vertical vibrations taken at a point 3 m from the CM 13 compactor which was operated through a range of frequencies.

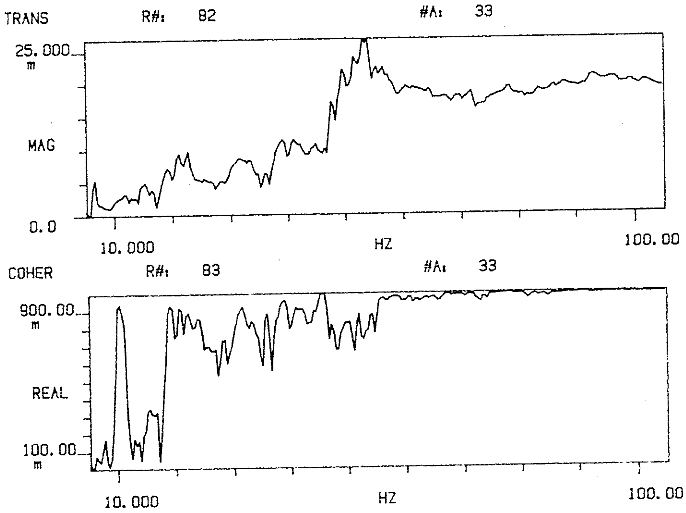

Figure 5 Transfer and Coherence Functions

The upper plot on Figure 5 presents the transfer function which increases somewhat regularly up to a peak at just over 50 Hz before settling down to a regular value for higher frequencies. The velocity and acceleration measurements which produced this result were not calibrated and so the plot represents a trend but is not quantitative.

The lower plot presents the coherence function for the same data over a vertical range from 0 to 1.

4. RESULTS

The data relating peak particle velocity with distance from the source for each compactor are presented on Figure 4. The relationship between energy in the spectrum was determined as part of the study but has not been presented in this report.

From the tests conducted on the actual compactor plates, vertical plate velocities were obtained as presented below.

MACHINE	PLATE VELOCITY (Vertical)
CM 13	1290 mm per/sec peak
ATN 1000	504 mm per/sec peak
DVU 4001	537 mm per/sec peak
ATS 6002	617 mm per/sec peak

Energy readings from the total spectra for the plate vibrations were also determined but again have not been presented in this report.

The transfer and coherence functions have already been presented in Figure 5.

5. DISCUSSION

The data on Figure 4 relating peak particle velocity with distance from the source is of primary interest in that it may be used to relate the structural and human response to these four individual compaction units operating on a body of medium sand.

Comparison with the DIN 4150 maximum particle velocity criteria of 8 mm/sec for a structurally sound building suggests that any of these compactors could be operated within 2 metres of such a structure without causing damage. However it is important to note that the presence of a high water table or a strata such as rock would reflect the input energy and enhance the vibration levels at the surface. Similarly a very dense material will transmit energy more efficiently than one with lower density as is evident as the soil densifies with compaction. All of these points suggest that in practice it would be mandatory to operate at a distance greater than 2 metres from a structure to minimise the probability of damage from the compaction process.

If the structure is already cracked (as are the vast majority of masonry structures) or in a state of incipient cracking, then lower velocity criteria would apply and the compactors would need to be operated at distances of up to 6 metres or more to minimize the probability of damage occurring.

The full analysis of data has shown that the velocity components in all three orthogonal planes are of similar magnitude. As such a measure of the vertical velocity used to measure human response can be obtained by dividing the peak particle velocity by $\sqrt{3}$. Reference to Figure 2 suggests that at 15 metres the vibrations from most compactors would be clearly perceptible in terms of human sensitivity. This should suggest that compaction in the vicinity of an inhabited residence is going to alarm the occupants and operators would be well advised to inspect and fully document any cracks in existing structures before undertaking compaction with a plate compactor.

It is of interest to note on Figure 4 that the peak particle velocity increases progressively for the machines ATN 1000, DVU 4001 and ATS 6002 which have increasing mass and rated power. However the highest peak particle velocities were produced by the CM 13 which is the lightest of four of them. It is believed that this is partly related to the operating frequency of the machine which for the CM 13 is of the order of $2\frac{1}{2}$ times the operating frequency of the others and also possibly related to the mode of movement of the plate.

It was suggested in the introduction that the body waves decay in proportion to the square of the distance from the source while the surface waves decay in proportion to the square root of this distance. On the basis of this it would be expected that the dissipation of peak particle velocity resulting from a combination of these waves would occur at a rate somewhere between the inverse square root and the inverse square of the distance from the compactor. In fact, as can be seen from the equations on Figure 4, the dissipation rate is on average a function of the simple inverse of this distance.

It is believed that the higher particle velocities achieved at higher operating frequencies is mainly due to two contributing factors. The data obtained from the accelerometers mounted on the compactor plates determined that the peak plate velocity of the CM 13 exceeded that of the much bigger ATS 6002 by nearly 100%. Furthermore the total energy input per unit time for the CM 13 exceeded that from the ATS 6002 by some 50%.

It is also thought that there is a significant frequency dependence on soil response and transfer of energy as suggested in the data presented in Figure 5. However the accuracy and quality of the Transfer Function data is questionable in that the complete and uniform coverage of the frequency range was difficult to obtain in the field and the number of data points averaged in the spectral analyser rather low. Further work is required on this aspect of the work.

Although the results of this study indicate that the surface particle velocities resulting from the operation of the CM 13 compactor are considerably higher than those of the larger machines, data published on the compactors indicates that the effective compaction depth of the CM 13 is less than that of the larger units. This may in part be due to the much larger surface area of the plate producing a larger stress bulb for the larger compactors than for the smaller ones. In any event, presuming the published data to be correct, the thicker lifts permitted for the larger compactors have obvious attractions for use in the field.

The higher velocities measured in this study for the CM 13 compactor when compared with the larger compactors do not appear to correlate with the human response as assessed subjectively in the field. It would appear that the vertical particle velocity criteria suggested are not singularly adequate and that further work is required on this aspect.

6. CONCLUSIONS

Data have been obtained for a range of vibratory plate compactors relating the decay of surface vibrations with distance from the compactor when operating on a deep body of medium dense sand. It was found that the peak particle velocity dissipated approximately in inverse proportion with distance from the compactors.

Vibrations have been expressed in terms of peak particle velocities since most authorities now agree they are the most appropriate criterion to be considered in the study of damage from ground vibrations.

A literature survey has determined that the lowest limiting velocity criteria against structural damage caused by steady state vibrations on sand are presented in a German code

DIN 4150. Although they are the lowest values available, practical experience suggests that they are not overly conservative.

The peak particle velocities measured in this study may increase (substantially?) in the field in conditions other than as tested here. In particular, a stratum below the surface reflecting the body wave energy to the surface or a denser body of sand would increase the level of the surface vibrations.

Further work remains to quantify these effects and in the meantime a generous margin for safety should be applied to the data in Figure 4 when assessing safe operating distances from existing structures. Operators should be conscious of the much more sensitive human response to vibration and fully survey adjacent structures before undertaking compaction operations.

It has been suggested that a small compactor operating at a higher frequency than the heavier compactors is more "efficient" in terms of surface energy transfer in the conditions under test. However further work is necessary for this to be proven.

7. ACKNOWLEDGEMENTS

Much of the work reported here was undertaken by Mr. D. Van Noort towards his final year Civil Engineering Honours thesis. Coates Hire Service kindly loaned the compactors used for the project and Mr. R. Emslie of VIPAC and Partners provided assistance in the understanding and analysis of the vibration data.

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