Effect of Vibratory Compaction Equipment on Cement-Mortar Lined Steel Water Pipe

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Abstract

Vibratory rollers are widely used on construction sites for their efficiency and effectiveness when compacting soil. However, according to Australian Standard AS2566, rollers are prohibited from being used near buried cement-mortar lined (CML) steel water pipes because it is believed that they may cause harm to the lining, when close by. This necessitates the use of non-vibratory compaction methods, increasing construction costs and time. The aim of this project is to study attenuation of vibration through ground due to vibratory rollers and its effect on lining of steel pipes, and determine a particular safe distance in terms of depth of the pipe and proximity of the roller. A field experiment was undertaken in Kwinana to measure the vibration levels on buried lined pipes, with varying pipe embedment depth. Through crack mapping of the lining, it was found that none of the existing cracks grew larger than the allowable crack size of 2mm. Also, on average, the low amplitude setting on the roller reduces the vibration levels by ~31% (compared to high amplitude). According to German Standard, DIN4150: Structural Vibrations, 80mm/s of vibration is permitted on the cement lining and applying this recommendation, a bedding height of 900mm is suggested for the experimental soil quality and roller (at high amplitude). In this project, a model is under development to recommend minimum bedding height for varying roller frequency and amplitude.

1. Introduction

Engineering construction processes such as piling, blasting, dynamic compaction and demolition produce vibrations in the ground and adjacent structures to varying degrees. With the increasing size and power of modern construction plant, its potential to cause damage or disturbance to sensitive structures needs to be evaluated. Along with a growing requirement for assessment of environmental impacts of such machinery, it is also important to understand the effects of vibratory compaction equipment. While there is a need to minimise the adverse effects of construction works, over-conservative restrictions on vibration may lead to significant and unnecessary cost increases in project construction.

Vibratory rollers are very popular for compacting dirt, soil, gravel and sand. Such machines, if used within close proximity, may cause harm to buried mortar-lined steel pipelines, particularly to the cement-mortar lining. According to the AS2566.2: 'Installation of Buried Flexible Pipelines', vibratory rollers are not allowed to compact the soil above or near the existence of a flexible buried pipeline. These restrictions are imposed under the perception that vibrations can damage the cement mortar lining (CML) inside the pipelines. The toughness of the lining is considerably lower than that of the steel pipes, making it vulnerable to cracks, which can eventually turn into chipping and breaking. The presence of the cement lining is vital to protect the steel pipelines from corrosion (Dunford 2008). Thus, any damage to the lining will affect steel pipes in the long run by accelerating the corrosion process.

Sun *et al* (1984) performed numerous experimental and field tests on CML carbon steel pipes. Various static and dynamic tests were carried out to structurally qualify the cement mortar lined carbon steel pipelines. The results demonstrated the linings to be flexible and "the three-edge-bearing tests showed that it only fell after the formation of plastic hinges in the steel". They also stated in the article that the cracks in the lining did not influence its failure patterns.

The effect of vibratory rollers on the linings also depends on the distance between the roller and the pipe, the effectiveness of the curing procedure in the lining operation, the variable specifications of the rollers (such as mass, drum width, amplitude, etc), and the duration that the roller was within close proximity to the pipe (Crabb et al 2002).

The main objective of this research is to gain a better understanding concerning the impact of vibratory rollers on cement lined steel pipelines. Additionally, the aim is to determine a particular safe distance in terms of depth of the pipe and proximity of the roller, with given soil properties and roller specifications. This would help guide future standards governing the use of vibratory compaction machines. This will also guide the control and mitigation of vibration to prevent damage or intrusion without the imposition of over-conservative limits.

2. Field Experiment Set-up

To achieve the objectives, a field experiment was conducted in Kwinana, at the Tyco Water site in mid-April 2010. Vibration levels on the cement lining were determined through the use of vibratory rollers that were passed over the pipe. The roller specifications are described in Table 1. The pipe used for the experiment (Figure 1) was a 1400mm diameter, 18 months old, mild steel cement lined (MSCL) pipe with 18mm of cement lining. The vibrations were measured using 2g (Figure 3: labels 1 to 4) and 5g (Figure 3: label 5) accelerometers (g=gravity), placed on all four sides at the centre of the 12m long pipe.

Roller Specifications – Single drum, smooth vibratory compactor	
Weight	11,414 kg
Vibrating frequency	32 Hz
High Amplitude	1.8 mm
Low Amplitude	0.9 mm
Drum width	2130 mm
Drum diameter	1524 mm

Table 1: Vibratory roller specifications

Figure 1: CML Pipe buried in ground

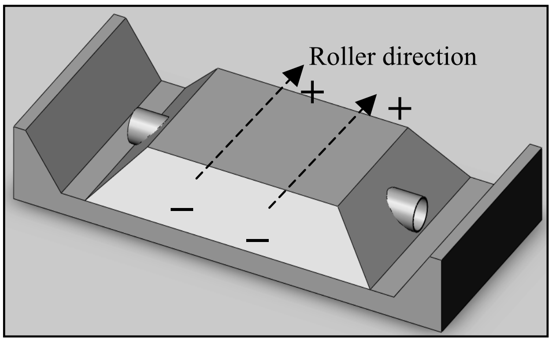

Figure 2: Isometric view of the setup

The initial soil cover above the pipe was 750mm. The pipe embedment depth was decreased by 150mm after 4 passes by the roller, at different amplitudes (high and low), to observe how vertical and horizontal distance between roller and pipe contributes to lining vibrations. Figures 1 and 2 above show the set up of the pipe and the roller movement. The lining cracks inside the pipe were also mapped, and the crack widths measured with a feeler gauge after every set of runs at each depth. After all the runs were completed and with little damage to the lining, the vibratory roller was statically placed on top of the pipe with 50mm cover and turned on at high amplitude setting for approximately 5 minutes.

3. Results and Discussion

3.1 Experimental results

Figure 4 illustrates the attenuation of vibration at accelerometer position 5, as the roller passes over the pipe. It shows the vibration mostly amplifying between +/- 1m, measured from pipe centreline. Plots of the measurements from the accelerometers located at the top and sides of the pipe indicate four distinct peaks – for the four different passes the roller made over the pipe. However, it was found that the vibration levels were not highly significant at accelerometer position 2.

The peaks were averaged and Figure 5 shows the maximum vibration levels (in mm/s) at the top of the pipe (position 4/5) vs. bedding height, at low and high amplitudes. As expected, vibration increases as the distance between the roller and the pipe decreases vertically. On average, the low amplitude setting on the vibratory roller reduces the vibrations by ~31% (when compared to high amplitude).

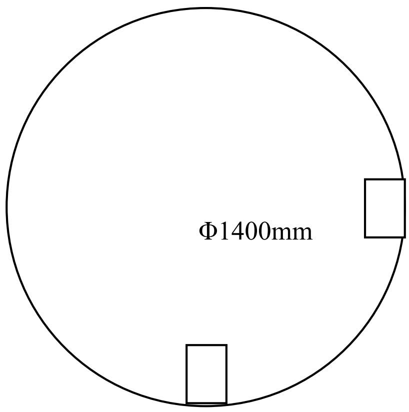

Figure 3: Accelerometer locations

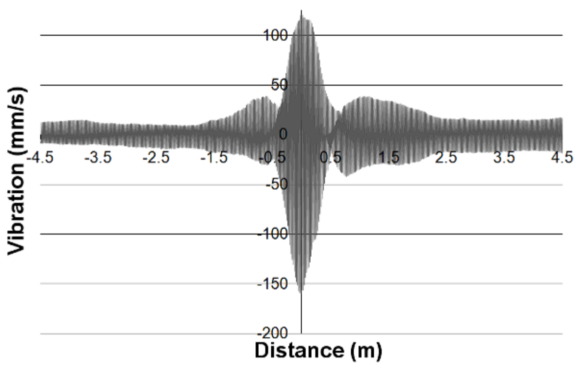

Figure 4: Vibration attenuation over the pipe

Figure 6 displays attenuation of vibration (at high amplitude setting) vs. horizontal distance from pipe centreline. The plot also displays the curve fitting equations and graphs using exponential function. It can be noticed that for 150mm bedding height, the vibration reduces by a factor of 0.5 from the pipe centreline to a distance of 0.7m away from the pipe. All curves approach a single value at 2.5m from the pipe.

Through crack mapping, it was found that circumferential cracks increased in width at an average of 0.2mm while longitudinal cracks increased at an average of 0.1mm. Overall, none of the existing cracks grew larger than 1mm after several roller passes were made, and very few new cracks were formed. According to Tyco Water, cracks up to 2mm wide in potable water pipelines need not be repaired as they will close and heal when immersed in water. When rewetted, the mortar typically absorbs up to 8% moisture and expands, and the cracks are reduced by 50%. Further hydration closes the cracks in a process referred to as 'autogenous healing'. Due to the final run of roller at 50mm soil cover, the lining chipped at many places but was still intact and did not fail.

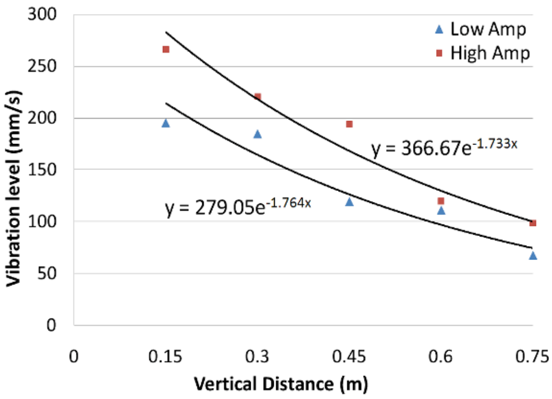

Figure 5: Vertical vibration attenuation

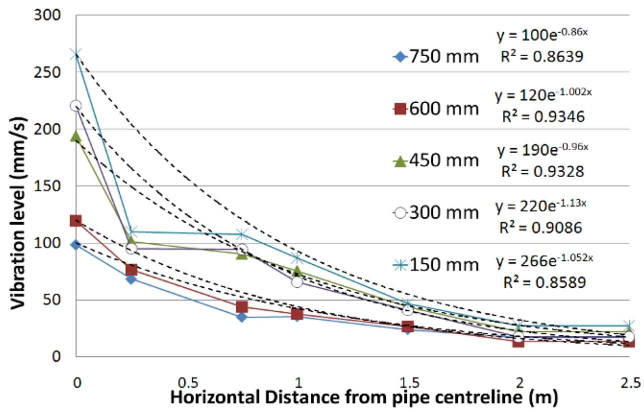

Figure 6: Horizontal attenuation for varying soil height (high amplitude) with exponential graphs

3. 2 Recommendation based on German Standard

German standard DIN 4150: Structural Vibration, Part 3: 'Effects of vibration on structures' specifies a method of measuring and evaluating the effects of short and long term vibration on structures designed primarily for static loading, including buried pipework. Section 3.4 in DIN4150-3 describes short term vibration as: "Vibration which does not occur often enough to cause structural fatigue and which does not produce resonance in the structure being evaluated". Otherwise, it is defined as long term vibration.

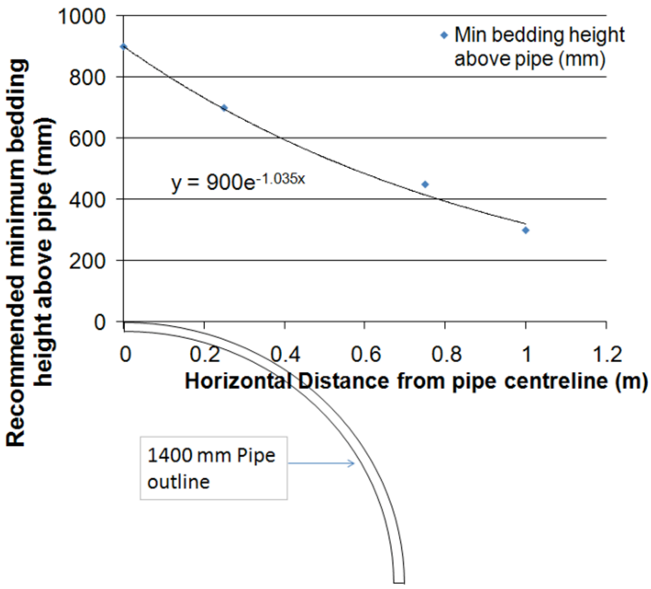

Figure 7: Recommended cover for buried pipe vs. Horizontal distance from pipe

For short term vibrations, the guideline value (according to German standard DIN 4150) for vibration velocity to be used for steel and concrete are 100 and 80mm/s respectively. Even though cement lining is not mentioned, it is safe to assume the behaviour of the mortar to be similar to that of concrete. Restricting the vibration levels to 80mm/s, Figure 7 displays the minimum cover for varying distance from the pipe. A minimum cover of 900mm is recommended to allow the vibratory roller directly above the pipe.

A hammer test determined the resonant frequency of the pipe as ~140Hz, which is well above roller frequencies that range from 25-40Hz. Thus, resonance of the pipe is not a problem in this case. Furthermore, these vibrations are temporary and unlikely to cause fatigue, and thus can be classified as short term.

3.3 Proposed Model for Vibration Prediction

The aim of the predictive model is to utilise easily available roller specifications, and recommend a minimum bedding height above the pipe based on maximum vibration levels allowed according to German Standard DIN4150. The required inputs are: roller frequency, number of vibratory drums and amplitude of the drum. The output will provide a vibration attenuation graph, along with the minimum bedding required that does not allow the vibration on the lining to exceed 80mm/s. A decrease in frequency, increase in number of drums and increase in amplitude is likely to enlarge the vibration levels experienced by the lining.

However, there are other governing factors that also affect vibration attenuation and are vital to the model. Vibration energy propagation through ground, from the source to the pipes, is dependent on two main wave types generated: surface waves and body waves (Kim 1999). The amplitude of these waves attenuates with distance from the source due to geometrical attenuation (expansion of wave front) and material damping (dissipation of energy within the soil itself) (Amick 2000). The rate of geometrical attenuation depends upon the type of wave and the shape of the associated wave front. Material damping in soil is a function of many parameters such as soil type, moisture content and temperature. For example, wet sand attenuates less than dry sand. It is also known as the loss of energy of the waves that is required to overcome friction between the soil particles.

Equation 1 (Amick 2000) below models the propagation of ground vibration between two points: a and b, where r is the distance from the source and v is the vibration level.

$$v_b = v_a \left(\frac{r_a}{r_b} \right)^{\gamma} e^{\alpha (r_a - r_b)} \qquad [1]$$

γ is dependent on the geometric attenuation, and can be determined by the type of wave, or the soil type. Correspondingly, α is dependent on material attenuation and thus varies on properties of the sand/clay being compacted.

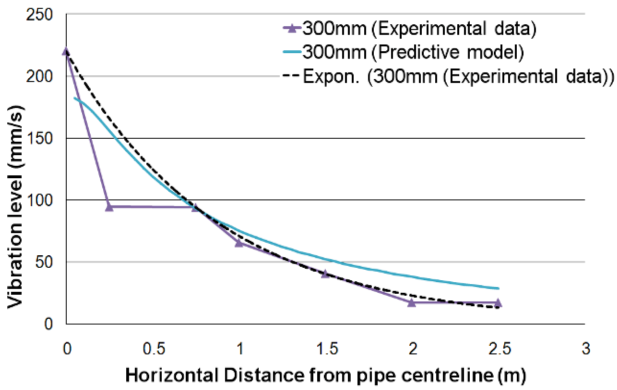

Figure 8: Vibration level for experimental and predictive data

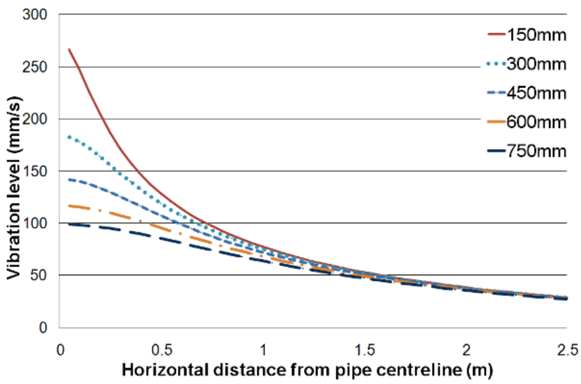

Figure 9: Vibration attenuation from the predictive model for varying bedding heights

Figure 8 shows the graph for 300mm bedding height. It displays the experimental result, exponential graph fitted on the experimental data and the plot from predictive model (where γ =0.5; α =0.3). Though not exact, the model follows similar pattern to that of experimental results. Figure 9 displays how the model predicts vibration at varying bedding heights to eventually attenuate to a particular vibration level i.e. all plots provide the same vibration level after ~1.5m. A similar outcome can also be noticed for experimental results in Figure 6.

3.3 Limitations

Both the model and the experimentation have a number of limitations. The tests were undertaken with an empty pipe. Typically, since these pipes will contain flowing water, it is likely to create a damping effect and thus protect the lining further from high vibration levels.

In addition, the lining in smaller diameter pipes has higher strength and thus will perform even better under same circumstances.

In the model, values for α and γ are difficult to determine unless tests have been previously carried out on the soil. Furthermore, equation 1 does not account for the fact that continuous compaction will constantly change soil density, and thus have an effect on attenuation of vibration. It does not account for the effect of pipe length and diameter.

4. Conclusions and Future Work

In summary, vibratory rollers are not detrimental to the cement lining, especially because the exceptionally high vibration levels are extremely short term. Applying a low amplitude setting, instead of high amplitude, can decrease vibration by ~31%. Even at high amplitude, for the given roller frequency of 32 Hz and amplitude of 1.9mm, soil bedding height of 900mm is recommended to be sufficient to drive the vibratory roller directly over the pipe. Furthermore, crack mapping of the lining also revealed that existing cracks did not grow wider than the tolerable width of 2mm. However, this study was based on a centrifugally spun, 18month old cement lining. Caution needs to be taken when applying these results to much older and deteriorated linings.

Sieve test analysis and minimum/maximum density tests will be performed on the soil samples from site to determine the soil properties. Further study needs to be carried out regarding effect of high vibrations on older and longer pipes.

5. Acknowledgements

The authors wish to acknowledge the help of John Breen (UWA Technical Staff) with the experimentation and all personnel at Tyco Water, especially Reg Williamson and Richard Galliot, for their support with the experimental procedure.

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