A CASE STUDY OF DAMAGE EFFECTS TO RESIDENTIAL BUILDINGS CAUSED BY VIBRATORY COMPACTION EQUIPMENT

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Abstract

This paper presents the findings into a study of vibration magnitude versus potential damage caused by vibratory compaction equipment at two residential properties located in South Australia. The two residential properties under investigation are classified as 'Contributory' in the local Historic Conservation Policy Area by Council and were constructed between the late 1800's and early 1900's. Vibratory compaction equipment was operated near to the properties at varying distances and machine settings with the primary objective to relate the measured vibration magnitude to cosmetic or structural damage, and to compare the results to the German Standard DIN 4150-3, 1999, *Structural vibration – Part 3: Effects of vibration on structures*. The secondary objective was to relate the measured vibration magnitude to subjective human perception and other observed ancillary effects to assist with community consultation activities that occur as part of major infrastructure projects. The results from the two objectives are presented and discussed in this paper.

1. Introduction

Vibratory compaction equipment, such as vibrating smooth or padfoot drum rollers, are a well-recognised source of vibration with potential to cause damage to sensitive structures situated close to construction works where vibratory soil compaction is required. In South Australia, German Standard DIN 4150-3 [1] is referenced in the Department of Planning Transport and Infrastructure (DPTI) *Environmental Instruction 21.7* [2] for the assessment and management of vibration generated by construction activities associated with infrastructure projects. Community members that are situated near to major construction works often raise concern regarding property damage, particularly if the vibration is felt or other effects perceived (e.g. rattling noises or visible movement of mirrors or water). Furthermore, potential vibration damage to structures with heritage value has also been a common concern for government agencies applying DIN 4150-3 and an Australian definition of a heritage structure.

With this context, the authors were presented with a rare opportunity to study the vibration damage effects for two residential properties that were planned for demolition to make way for a major infrastructure project. The primary objective for the study was to relate measured vibration magnitudes to cosmetic or structural damage that could occur, and to compare the results to the DIN 4150-3. The secondary objective was to relate the measured vibration magnitude to subjective human perceptions inside and outside the dwelling during vibratory compaction activities. The intent of the secondary objective was to assist with community related discussions that occur as part of major infrastructure projects.

2. Description of Properties Tested

47 Elizabeth Street was a single storey residential property located on the corner of Elizabeth Street and Cedar Avenue, Croydon, SA, 5008. 4 Day Terrace was a single storey residential property located in West Croydon, SA, 5008. The soil in this area of Adelaide comprises Red-brown clay or Sandy clay soils.

The dwellings under test were constructed in a period from late 1800’s to early 1900’s. The floor plan of each dwelling was a four-roomed layout, with an out-house extension at the rear, containing the kitchen and bathroom or laundry. The four, formal rooms at the front were separated by a central corridor. The external wall construction at 47 Elizabeth Street was typical for this era of residential building in South Australia and was a double skin of masonry, separated by a 50mm cavity, giving an overall wall thickness of 270mm. The windows systems were typically vertical sliding sash types (i.e. double hung). Footings were typically located on crushed rock or soil (i.e. clay or sandy soil) foundations. Of note, the extension at the rear of 47 Elizabeth Street was of a more modern brick construction with a solid concrete foundation, and the overall wall thickness at 4 Day Terrace was 230mm, which indicates that there was either none or minimal cavity in the wall construction for this building.

3. Testing Procedure

3.1 47 Elizabeth Street

The vibration source used for testing was a BOMAG BW 211 D nominal 10 tonne vibratory roller with the following four operating modes (Roller Modes):

A. Low engine revolutions and low vibration amplitude
B. Low engine revolutions and high vibration amplitude
C. High engine revolutions and low vibration amplitude
D. High engine revolutions and high vibration amplitude.

Calibrated AvaTrace M60 vibration monitoring loggers were utilised for testing. Vibration monitoring was carried out at the locations described in Table 1 and shown in Figure 1. Five roller locations were tested, namely 13m, 8m, 5m, 2m and 0m from the nearest point of the roller to the rear facade of the dwelling. The roller was generally stationary for tests.

3.2 4 Day Terrace

The source used for testing was an AMMANN ASC 170 D nominal 18 tonne vibratory padfoot roller with the same four operating functions as the previous test at 47 Elizabeth Street. Calibrated AvaTrace M60 and Instantel Minimate vibration monitoring loggers were utilised for testing.

Vibration monitoring was carried out at the locations described in Table 2 and shown in Figure 2. Note that the two dwellings to the east of the property had been demolished, which allowed an operating area for the padfoot roller. A number of various roller locations and operating directions were tested, as summarised in Table 4. Note that the padfoot roller was unable to oscillate the drum in a stationary position and therefore was required to move forward and backward at a specific distance for the tests.

Table 1. 47 Elizabeth Street measurement descriptions

Monitoring Location	Measurement Description
1	The tri-axial geophone was mounted onto a spike, which was inserted in the ground adjacent to the eastern facade of the dwelling.
2	The tri-axial geophone was mounted onto the base of the wall of the eastern facade of the dwelling. A second, single axis geophone was mounted approx. 1.5m above ground level on the same facade.
3	The tri-axial geophone was mounted onto the base of the wall of the northern facade of the dwelling. A second, single axis geophone was mounted approx. 1.5m above ground level on the same facade.
4	The single axis geophone was mounted onto the wall at a height of approx. 1.5m above ground in the bathroom of the dwelling.
5	The tri-axial geophone was mounted directly onto the middle of the concrete floor slab of the living room of the dwelling.
6	The tri-axial geophone was mounted onto the base of the wall of the southern facade of the dwelling.
7	The tri-axial geophone was mounted onto the ground adjacent to the boundary wall on the eastern facade of 60 Elizabeth St.

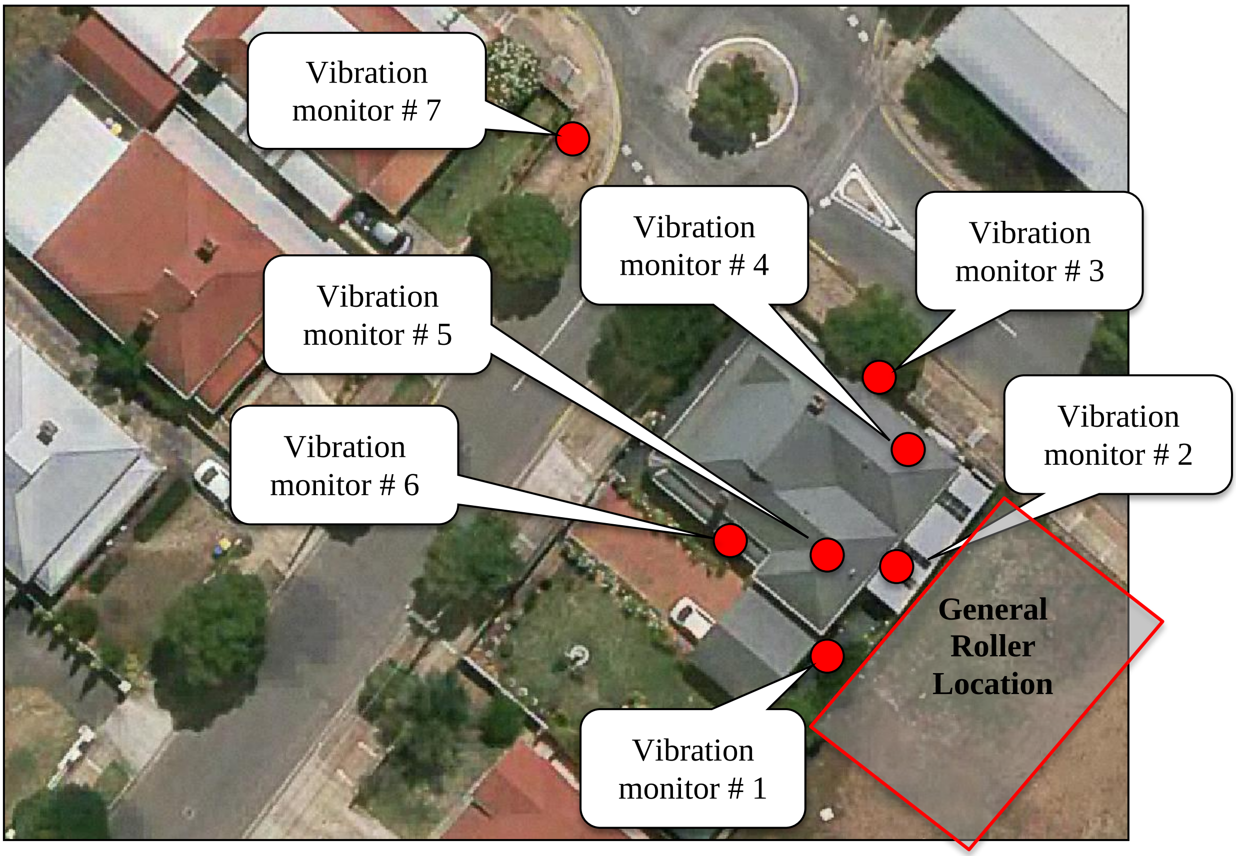

Figure 1. Monitoring locations – 47 Elizabeth Street

Table 2. 4 Day Terrace measurement descriptions

Monitoring Location	Measurement Description
1	The tri-axial geophone was mounted onto a spike, which was inserted in the ground adjacent to the eastern facade of the dwelling.
2	The tri-axial geophone was mounted onto the base of the wall of the eastern facade of the dwelling immediately adjacent position 1
3	The tri-axial geophone was mounted onto the internal wall of the bedroom of the property. The geophone was located at a height of approx. 1.5m above floor level.
4	The single axis geophone was bolted into the tiles on the ground at the southern facade of the property immediately adjacent Position 5.
5	The single axis geophone was mounted onto the base of the wall of the southern facade of the property immediately adjacent Position 4
6	The tri-axial geophone was placed at the base of the eastern facade of 6 Day Terrace.

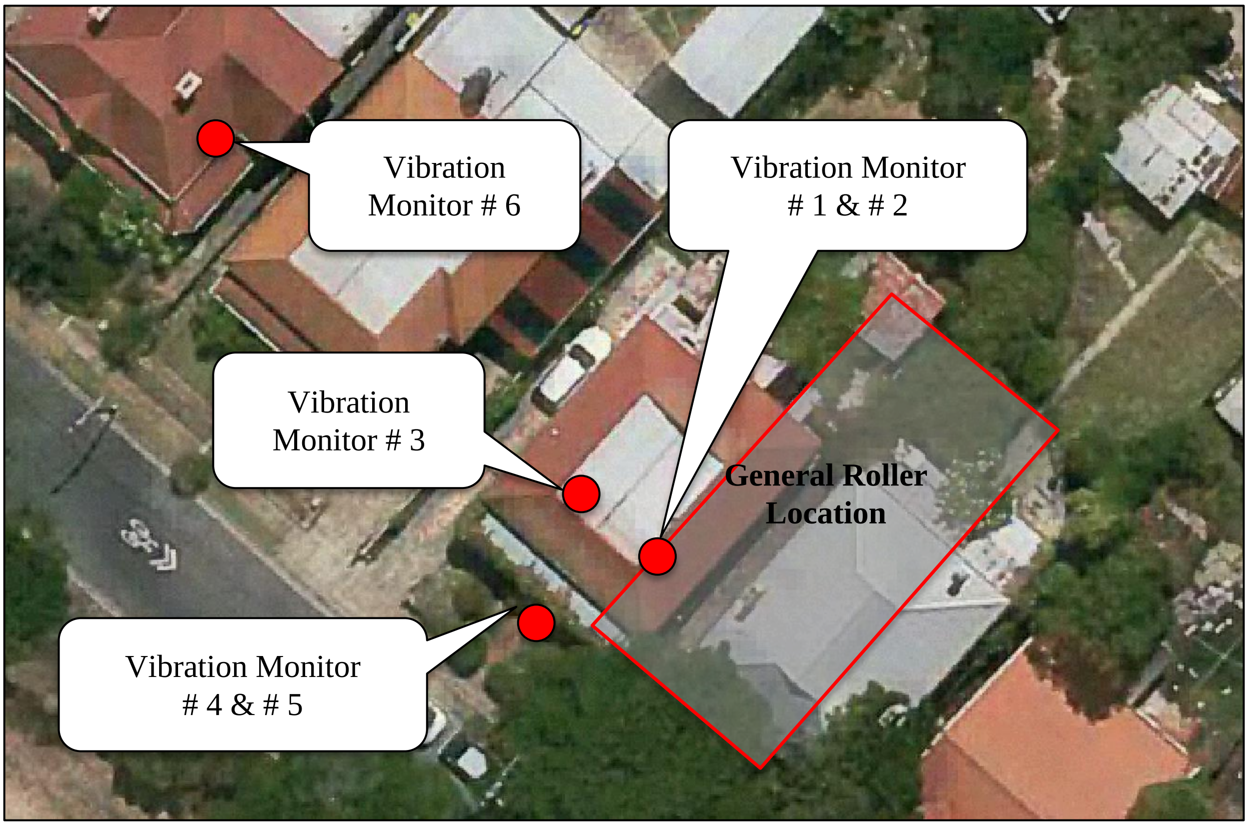

Figure 2. Monitoring locations – 4 Day Terrace

4. Results

4.1 47 Elizabeth St

Results from the vibration monitoring undertaken at 47 Elizabeth Street are presented in Table 3 below.

Table 3. Vibration levels at each monitoring location – 47 Elizabeth Street

Test Description		**Measured PPV (mm/s)**						
Test	**Location (Roller Mode D unless otherwise noted)**	**# 1**	**# 2**	**# 3**	**# 4**	**# 5**	**# 6**	**# 7**
1	Roller at 13 m from house. Mode C	3.4	1.4	1.9	4.6	1.1	2.3	0.6
2	Roller at 13 m from house.	5.4	1.8	4.4	5.5	2.3	2.9	1.0
3	Roller at 8 m from house.	12.7	2.6	4.4	7.9	3.1	2.7	0. 8
4	Roller at 5 m from house.	19.4	5.6	7.7	11.8	5.8	6.4	1.6
5	Roller at 5 m from house. (moving back & forth).	28.9	5.2	7.1	16.2	5.5	6.1	1.5
6	Roller at 2 m from house.	16.1	6.8	9.9	13.2	4.9	4.5	2.0
7	Roller close to house (centre of facade).	6.4	22.9	12.4	19.5	9.9	7.2	2.1
8	Roller close to house (near laundry).	22.3	15.3	13.9	27.9	4. 6	4.7	2.1

The vibration levels measured at monitor location # 1 were generally higher than levels measured at other external monitoring positions and significantly higher than those measurements taken at monitor location #2, which was located at foundation level at the facades closest to the source. This indicates that the vibration level reduced upon vibrational energy transfer to the foundation structure and therefore a ground-based measurement used in place of a foundation measurement is a conservative indicator when compared to DIN 4150-3. Additional post testing comments and structural analysis are also presented below. Two occurrences of possible damage were noted post testing. These were:

- in the rear laundry, minor plaster flakes were seen on the floor (Figure 3)
- at the front corner of the building (southern corner), a brick had fallen from the already damaged corner (Figure 4)

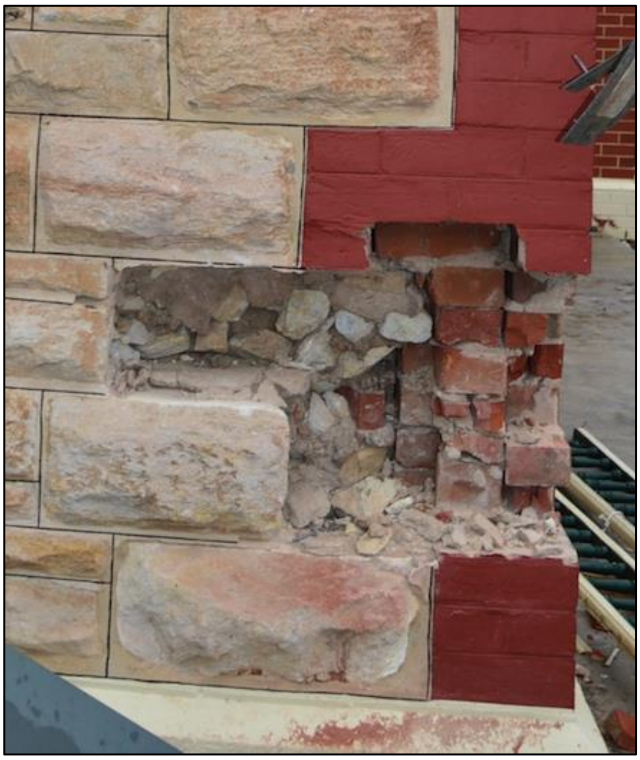

Figure 3. Damage with small flakes of plaster fallen from wall (already damaged by demolition works)

Figure 4. Damage with brick section fallen (already damaged by previous demolition)

Figure 5. Roller at 2m

Figure 6. Roller at wall

4.2 4 Day Terrace

Analysis of the results of the measurements undertaken at 4 Day Terrace provides a similar outcome to 47 Elizabeth St.

Table 4. Measured vibration levels at each monitoring location – 4 Day Tce

Test Description		**Measured PPV (mm/s)**					
Test	**Location (Roller Mode)**	**# 1**	**# 2**	**# 3**	**# 4**	**# 5**	**# 6**
1	Source 14 m from monitor #1. A	7.1	4.1	4.4	1.8	1.9	0.6
2	Source 14 m from monitor #1. C	5.5	3.1	6.4	1.7	2.1	1.4
3	Source 14 m from monitor #1. D	7.6	4.4	9.4	2.7	2.7	1.1
4	Source 7.5 m from monitor #1. A	6.7	4.2	11.2	2.8	3.4	0.7
5	Source 7.5 m from monitor #1. C	12.3	4.7	6.3	3.0	3.6	1.4
6	Source 7.5 m from monitor #1. D	12. 8	5.2	13.5	3.9	4.1	1.4
7	Source 1.7 m from monitor #1. A	20.4	7.1	24.4	8.3	9.1	2.0
8	Source 1.7 m from monitor #1. C	30.5	6.2	13.0	9.5	9.5	2.1
9	Source 1.7 m from monitor #1. B	20.0	7.0	15.3	9.7	11.5	1.7
10	Source 1.7 m from monitor #1. D	21.8	9.5	16.1	10.5	10.7	2.0
11	Source close to rear out-house. B	26.9	7.6	9.9	2.2	3.2	2.7
12	Source close to rear out-house. D	27.5	7.6	11.1	3.0	3.3	4.4
13	Source close to house. C	50.0	21.6	38.5	7.5	9.1	5.0
14	Source close to house. D	69.2	22.8	26.5	6.3	9.3	6.3
15	Source close to southern facade of house. A	10.1	5.0	13.3	20.6	27.8	6.1

Damage observed during the testing was as follows:

- An opening formed in the masonry wall on the eastern side of the out-house with bricks falling from the top section of the wall.
- A pre-existing crack below the window on the eastern facade continued to propagate and widen..
- Cracks formed on the inside corners of a room with audible ‘cracking’ type sound as the vibration level increased followed by a section of delaminated plaster falling from high up the internal wall closest to the roller location.

Figure 7. Cracked plaster (wall) and floor debris.

Figure 8. Crack observed below windowsill increased in size.

4.3 Subjective observations

In addition to the measured vibration levels presented for 4 Day Terrace above, a DPTI team member, in consultation with Resonate staff, noted various subjective observations over the testing duration. Observations noted were the observed vibration effects on various items placed around the house (e.g.

hanging mirror, wine glass filled with water placed on a table, wine bottle placed on the floor) as well the perceived whole body vibration response.

To provide guidance on how to rate the whole body vibration experience, human perception indicators were used to provide an increased level of understanding of the subjective response. The perception indicators utilised were taken from Ref. [3] and are as follows. The observation notes are presented in Table 5.

Perception indicators

1. Perception improbable
2. Perception probable
3. Clear perception
4. Very clear perception
5. Strong perception
6. Very strong perception
7. Not uncomfortable
8. A little uncomfortable
9. Fairly uncomfortable
10. Uncomfortable
11. Very uncomfortable
12. Extremely uncomfortable

Table 5. Subjective observations (based on Location 1 vibration levels)

Roller Mode	**Test Details**	**Measured PPV (mm/s) at Monitor #1**	**Indoor observations**	**Outdoor observations**
A	Distance from Monitor #1: 14m	5.5	Perception indicator = 6 Bottle and glass rattling more on table with lower frequency vibration and more noticeable inside than outside. Feel in walls and floor. No damage noted.	Perception indicator = 6 Can feel vibration in the ground, approx. same impact as for Test 1. No damage noted.
B	Distance from Monitor #1: 7.5m	12.3	Perception indicator = 9 Picture frames rattling on the wall, western facade window rattling very noticeably, wine glass rattling very noticeably. Audible cracking in paint and plaster of bedroom corner. Noticeable window rattling at both 5&6 Day Tce	Perception indicator = 8 Vision starting to blur at edges Can feel vibration further up through the body, would not like to endure for a long time. No damage noted outside. As above plus visually seeing walls moving. Chunk of plaster fell out of outside wall closest to monitor #1 and loose, cracking paint falling off.

Roller Mode	Test Details	Measured PPV (mm/s) at Monitor #1	Indoor observations	Outdoor observations
C	Distance from Monitor #1: 1.7m	20.4	Perception indicator = 10 Very noisy vibration in windows in kitchen and other windows throughout house. Feel vibration distinctly in floors. Door lintels vibrating visibly. Heavy mirror hanging on the wall vibrating noticeably. Wine bottle wobbling on floor and likely to fall. Wine glass fell off window sill in front bedroom. Not feeling nauseous but very uncomfortable, unacceptable conditions. Plaster cracking in bedroom further, small pile of dust on floor.	Perception indicator = 10 Roller is noisier and closer adds to perceived impact of vibration and overall level of comfort. Blurred vision and vibration through whole body Corrugated roof sheets rattling. Brick wall on out-house visually moving.
D	Distance from Monitor #1:1m perpendicular to middle (moving forward and back between 0m and brick wall)	50.0	Perception indicator = 11-12 Starting to feel nauseous. Table moving across the room in bedroom closest to monitor #1. Water splashing out of wine glass. Chunks of plaster falling off wall (where patched up for noise testing), further cracking in corner. All items in house rattling noticeably.	Perception indicator = 11-12 Starting to feel nauseous. Vision blurred. Vibration through whole body. Loose items on ground moving noticeably and loud rattling.

5. Discussion

Our summary of the key findings from this investigation, are presented below. Note that all indicated PPV levels are those measured at monitor #1:

- Ground vibration levels of 2mm/s PPV (~ 30 Hz forcing frequency) were easily discernable and subjectively annoying although tolerable.
- Ground vibration levels of 5mm/s PPV (~ 30 Hz forcing frequency) were very discernable with rattling glass and bottles on tables and audible re-radiated low frequency noise from the building structure. Subjectively this vibration level was considered disconcerting and barely tolerable during the day and certainly not tolerable during sleeping hours.
- 47 Elizabeth Street was subjected to ground PPV levels up to 22 mm/s @ ~30 Hz without any

cosmetic damage noted. This is because the section of building most impacted by vibration was relatively new with significant concrete foundations and modern masonry wall construction

- 4 Day Terrace was subjected to ground PPV levels up to 70 mm/s @ ~30 Hz with the following noted:
    - onset of cosmetic damage with minor paint/plaster 'hairline' cracking at 7 mm/s
    - major cosmetic damage was noted with delaminated plaster chunks falling to the floor at 50 mm/s
    - major structural damage of poorly constructed out-house masonry wall with vibration levels approximately 50 mm/s.
- 4 Day Terrace was more sensitive to the effects of vibration due to the relatively poor construction methodology compared to modern buildings. This era of building construction is likely to consist of footings located on crushed rock or soil (i.e. clay or sandy soil) foundations.
- The measured vibration level in the building structure as well as the subjective human response to whole body vibration was noted to be sensitive to the vibration forcing frequency. Generally, the lower the frequency, the greater the impact. A change of 7 Hz (i.e. from 35 to 28 Hz) was clearly noticeable.
- The results suggest that the prescribed vibration criteria in DIN 4150-3 and DPTI EI 21.7 are appropriate for dwellings in the Adelaide region. The test results indicate that exceedance of the recommended residential criteria (5 mm/s at low frequency) significantly increases the risk (or probability) for damage, particularly for older heritage type building constructions similar to that tested at 4 Day Terrace. As expected, more modern building structures, such as that tested at 47 Elizabeth Street, were observed to be significantly more resilient to vibration.
- Vibration measurements carried out on the ground for comparison to the criteria are conservative in comparison to the DIN 4150-3 requirements for measurements to be carried out on the outer wall foundations or outer wall. Measurements carried out on the ground (or similar) are generally favoured for practical reasons. For both of the dwellings tested, the measured vibration magnitudes generally halved at the outer wall foundations in comparison to those measured on the ground. Therefore, a measured level of 6mm/s PPV at the ground adjacent the foundation may generally be approximated as 3mm/s at the outer wall foundation.

6. Conclusions

It is concluded that the criteria specified in DIN 4150-3 are appropriate for residential dwellings located in the Adelaide region. Minor cosmetic damage was noted for ground measured PPV levels of 7 mm/s and major structural damage at approximately 50 mm/s PPV for vibratory roller induced vibration in a typical 100 year old Adelaide residence.

Acknowledgement

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References

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