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Assessment of Vibrations from a Seismic Test Facility

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ABSTRACT

The recent earthquakes in Christchurch led to the redevelopment of the University of Canterbury's Seismic Equipment Laboratory (SEL). The SEL facility will involve the testing of building structures subject to simulated static and dynamic displacements from earthquakes, with a reaction wall and floor used to exert loads by way of hydraulic actuators on test specimens, and shaker tables used to test built forms separately or in combination. These tests can generate significant ground vibration, which has the potential to affect the use of nearby buildings housing sensitive equipment. This paper will outline measurements and analysis carried out to predict the likely vibration levels at the footings and within adjoining buildings. It also outlines methods to mitigate vibration in excess of relevant criteria.

Keywords: Vibration, Earthquake I-INCE Classification of Subjects Number(s): 46.3, 49

1. Introduction

Aurecon was engaged as the structural engineer for the University of Canterbury's Engineering Department's redevelopment project. The project involves the upgrade of the Seismic Equipment Laboratory (SEL), with the specific test requirements for the laboratory. The proposed development is mainly a strong wall/strong floor testing facility i.e. a static reaction wall. The seismic shaker table may possibly be added in future.

Vibration generated from current quasi-static seismic tests using existing reaction frames can cause noticeable vibration in adjoining spaces within the Civil and Mechanical Engineering multi-storey building. To enable the assessment and prediction of vibration generated from the proposed new SEL facility, it is necessary to undertake a soil/structure vibration study to understand the level and spectral content of vibrations due to testing within the existing facility and transferred to the ground an into nearby buildings.

The proposed site for the new SEL facility is surrounded by the Student Services building, Rutherford building and Regional Science and Innovation Centre (RSIC). Some of these buildings hold sensitive equipment requiring low ambient vibration levels. Below is a list of sensitive equipment identified:

- NMR Spectroscopy suites
- Research Spectroscopy suits
- Laser microscope
- STM (Scanning Tunnelling Microscopy)
- Other microscopes / X-ray Crystallography requirements
- Ultra high precision Balances

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2. Seismic Test Facilities

The upgrade of the facility will see increased loads and increased occurrence of testing when compared to the pre-upgrade operations. It is proposed that at least 12 hydraulic actuators are required for lateral loading from the strong-walls, with an associated hydraulic pumping system, dedicated controllers, and a cooling tower for the pumps. The actuator will be used both for the slow pseudo-dynamic earthquake testing and the real-time earthquake testing, with typical setup shown below in Figure **1**.

Table 1 Recommended specifications for the hydraulic actuators

Type	Force (kN)		Strokes (mm)	Quantity
	Tension	Compression		
Static	500	500	+/- 250	2
	1000	1000	+/- 500	2
	2000	2000	+/- 500	2
Dynamic	100	100	+/- 250	2
	250	250	+/- 250	2
	500	500	+/- 500	2

Proposed operating conditions are:

- **Shaking table testing** on full capacity, namely, frequency range: 0-50Hz, maximum displacement: +/- 500mm, maximum velocity: +/- 1100mm/sec, and maximum acceleration with maximum specimen mass: 1.2g.
- **Large-scale quasi-static, pseudo dynamic or hybrid simulation testing** using all 12 actuators operating simultaneously at full stroke (four storey building loaded in two direction, two actuators in one direction, one actuator in the other direction).
- **Fatigue testing** with one 500kN actuator undertaking dynamic fatigue tests +/-250kN at 10Hz at +/- 10mm stroke.

Figure 1 Quasi-static Testing (ncree.org.tw)

3. Vibration Criteria

3.1 Human Comfort

Vibration induced by external sources such as vehicular traffic exciting the building structure is typically generated between 1Hz to 80Hz. The level of vibration is normally defined based on the level of perception. Multiples of the baseline perception curves are defined according to subjective acceptance (i.e. adverse reaction is unlikely). Guidance with respect to vibration limits for human exposure is provided in Australian Standard AS 2670 - Evaluation of human exposure to whole-body vibration. The standard specifies vibration limits using a number of criteria curves in terms of root mean square (r.m.s.) vibration velocity levels suitable for different building usages.

Table 2 – Vibration limits for human exposure

Place	Time	Continuous or intermittent vibration (refer to the curves from AS2670)	Transient vibration excitation with several occurrences per day (refer to the curves)	Vibration sensitivity	Description of Use
Critical working area (facility technical suites, precision laboratories)	All	1	1	Vibration is not felt by people but starts to affect equipment	Suitable for sensitive sleep areas. Suitable in most instances for microscopes to 100X and for other equipment of low sensitivity.
Residential	Day	2 to 4	30 to 90	Vibration is barely felt by people	Appropriate to sleep areas in most instances. Probably adequate for computer equipment, probe test equipment and low-power (to 20X) microscopes.
	Night	1.4	1.4 to 20		
Office	All	4	60 to 128	Vibration is felt by people	Appropriate to offices and non-sensitive areas.
Workshop	All	8	90 to 128	Vibration is distinctly felt by people	Appropriate to workshops and non-sensitive areas

Continuous or intermittent vibration resulting from the operation of the proposed Seismic Equipment Laboratory (SEL) should not exceed “curve 4” in the nearby office buildings. The magnitudes for transient vibration in offices should not be increased without considering the possibility of significant disruption of working activity.

3.2 Sensitive Equipment

Vibration criteria for sensitive equipment are often specified by manufacturers in terms of RMS velocity. In the absence of such information, the generic vibration criteria curves recommended by Gordon et al [1] and Amick et al [4] was used as guidance for designing laboratories or facilities containing vibration sensitive equipment. The generic vibration criteria are equivalent to BS 5228 [3] and ASHRAE [2].

The design aimed to ensure that vibrations due to the proposed Seismic Test Facilities operation would not exceed VC-A vibration criterion curve, i.e. 50µm/s in any one-third octave band in the nearby vibration sensitive facilities; with local vibration isolation of sensitive equipment should lower vibration limits be required.

4. Geotechnical Conditions

Multi-channel Analysis of Surface Wave (MASW) testing was undertaken to assess potential variability in soil stratigraphy with measurements of shear wave velocity across the site. Down hole geophysical testing was undertaken within the boreholes for in-situ measurement of shear wave velocity with depth.

MASW is a geophysical technique that uses non-destructive seismic method (i.e. dispersive nature of surface waves) to image the shallow subsurface (less than 100m depth). It analyses dispersion properties of certain types of seismic surface waves (fundamental-mode Rayleigh waves) propagating horizontally along the surface of measurement directly from impact point to receivers. Figure 2 below illustrates a typical Multichannel Analysis of Surface Waves survey setup.

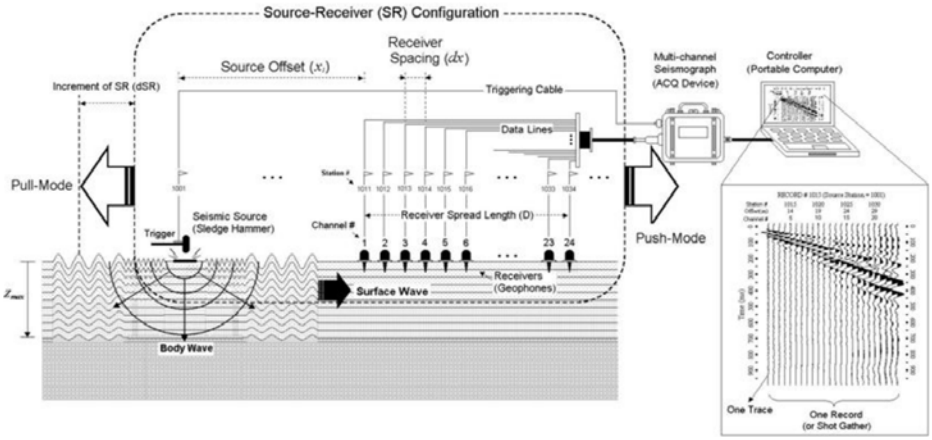

Figure 2 Typical MASW test setup

In this project, the source for the active survey was a 16lb sledgehammer impacting a 10kg aluminium plate. Twenty four (24x) 4.5Hz geophones mounted on metal brackets are deployed in an array and evenly spaced at 1m connected to a multichannel recording device (seismograph). Figure 3 shows the typical measured shear wave velocity profile versus depth at the project site.

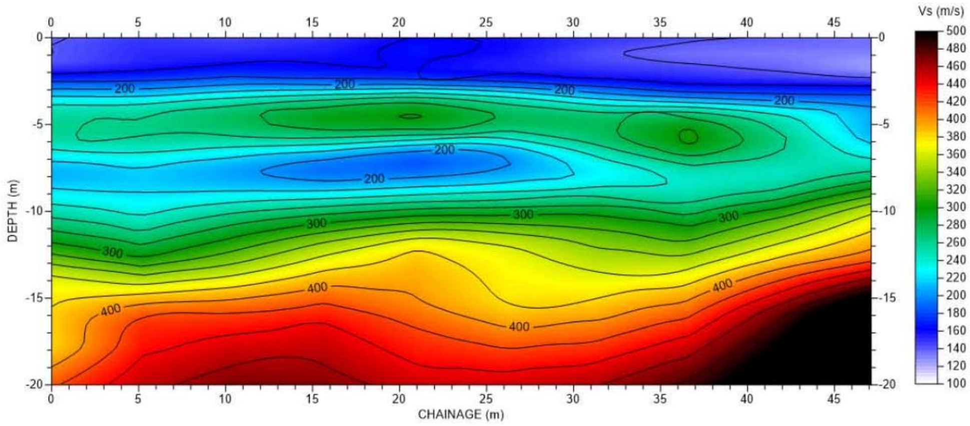

Figure 3 Section of shear wave velocity profile with depth

Test results are fairly consistent and suggested increasing velocity with depth in general. The key geotechnical parameters that have been considered in modelling include:

- Shear wave velocity is typically 120m/s to 200m/s to 5-7m deep, increasing to 300m/s at about 10m depth, and 500m/s at about 18m depth.
- Compression wave velocity is approximately double the shear wave velocity at depths noted above.
- Density is approximately 1800kg/m^3
- Spring stiffness is approximately 17kPa/mm at the centre of the proposed building
- Damping ratio for both shear and compression waves is 0.025

5. Ground-borne vibration

5.1 Wave Propagation

In general, attenuation of vibration with distance depends on the type and location of vibration source, the vibration amplitude and surrounding ground properties.

When a vibratory excitation source impacts the ground, energy is transferred from the source equipment to the ground. The energy reflects and refracts off the ground surface and subsurface interfaces between dissimilar materials in an intricate wave pattern. Vibration amplitude is reduced during propagation through the ground because of geometric and material damping.

Generally, the amplitude of ground-borne vibration energy decreases with distance from source, and vibration of higher frequencies decay faster than those of a lower frequency. Vibration attenuation can be described by the following equation:

$$V_2 = V_1 \left(\frac{R_1}{R_2}\right)^{\gamma} e^{-\alpha(R_2 - R_1)}$$

$\gamma = 0.5\ for\ R\ waves\ or\ \ \gamma = 2$ for P or S waves

$V_1 =$ the particle velocity at distance R_1

$V_2 =$ the particle velocity at distance R_2

$\alpha =$ attenuation coefficient (m^{-1}), which increases with dominant frequency

5.2 Computational modelling of vibration energy

Modelling of dynamic loads imparted into the soil was carried out using the MATLAB with functions provided by the Elasto-Dynamics Toolbox (EDT) to model wave propagation in layered media, which are often integrated within similar software such as Pipe-In-Pipe to assess ground vibration from vibration sources (eg. Rail lines at grade or within tunnels). EDT uses the direct stiffness method and the thin layer method to model waves in layered media. Both methods are based on a decomposition of the wave field into a series of problems governed by plane wave propagation. Examples of the real and imaginary components of displacement across the site using the geotechnical conditions outlined previously are shown below in Figure 4.

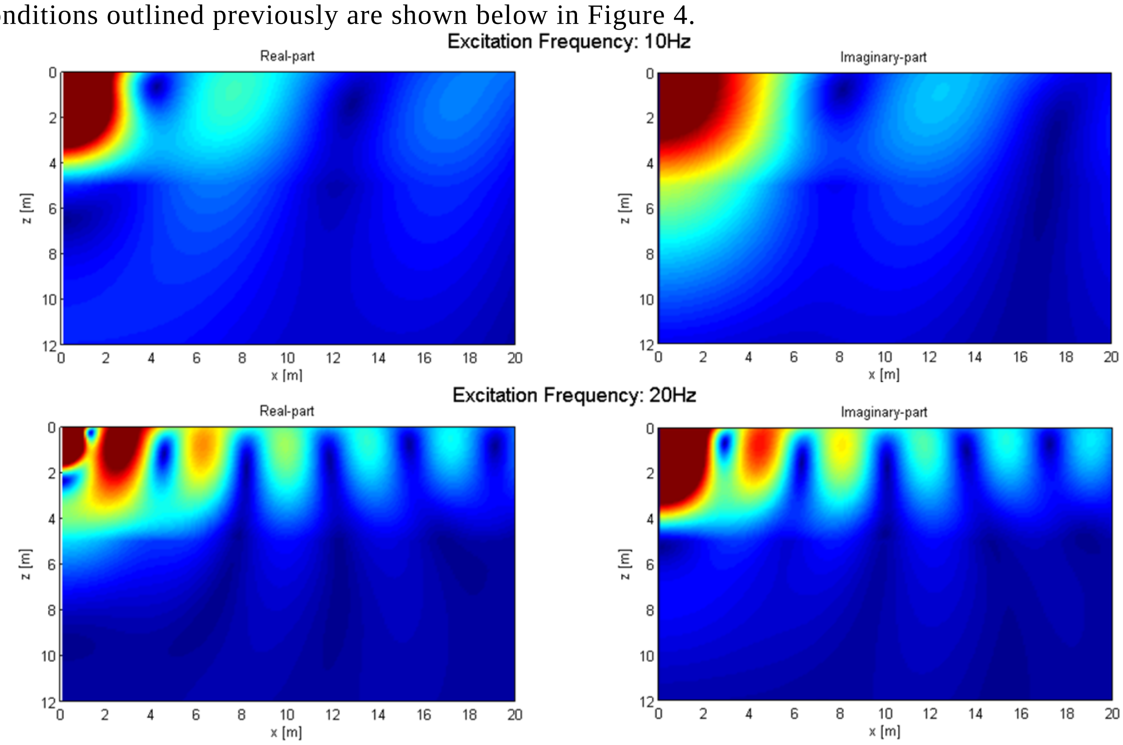

Figure 4 Real/Imaginary components of displacement due to a unit load at (0,0) cycling at 10Hz and 20Hz.

6. Vibration Survey – Impulse response test

Rather than rely on computational modelling methods to predict energy transfer from a vibration source on the ground, transferred into neighbouring buildings, it was considered more accurate and simpler to measure resultant vibration from a quantified energy source (impulse).

Survey of the ground-surface vibration response of the project site was carried out to understand ground attenuation of vibration components (shear, Rayleigh, compression waves) for the site and compare with geotechnical conditions recently investigated (soil elasticity and stratification).

A vibration pulse was created by dropping a heavy weight (i.e. 16 tonne load from a known height of 1m and 1.5m height) on the ground to simulate ground vibration for the new seismic laboratory, and tri-axial vibration measurements were extensively undertaken at various locations simultaneously at the following locations:

- within other areas of the existing building;
- within areas of nearby buildings (maximum of 3 buildings – Rutherford, Student Services, RSIC early works stage);
- Ground-borne levels at various distances from the existing building (up to 5 points).

Figure 5 Impact testing using 16 tonne weight and an array of tri-axial accelerometers

To understand the characteristics of propagating wave, the amplitudes of vibration response at the above mentioned locations were recorded using 3D geophone(s) at a sampling rate of 200Hz continuously over time during the test. Recorded signals were passed through a low pass filter cutting away irrelevant and undesired signals above 80Hz (caused by the accelerometer resonance and electronic noise etc.). The measurements have been analysed and raw data was post-processed in MATLAB. Figure 6 shows the time histories and spectra of the measured vibration response at typical locations:

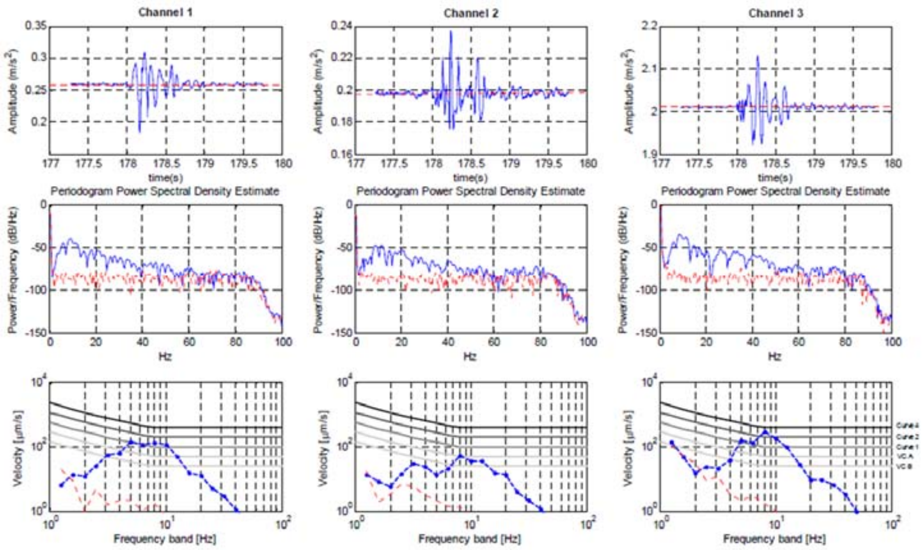

Figure 6 Typical measured ground-vibration response (Blue) vs background level (Red)

7. Assessment

Our assessment has considered the relative energy imparted by that of the test impact (16 tonnes dropped at 1.5m height, with a potential energy of 240kJ), with the shaker table (40 tonnes at 1.1m/s, with a kinetic energy of 20kJ) and the proposed large scale Effective Force tests (assumed to simulate earthquake ground accelerations up to 1g above 1Hz, with test structures up to 5 tonnes, e.g. Masonry wall elements).

Acceleration in the vertical direction dominated the results (as expected given the majority of energy is contained within surface or Rayleigh waves). This is also consistent with results found by others such as Dong-Soo Kim and Jin-Sun Lee (2000). Building vibration is typically 100th of that measured in the Rutherford building from an impact with energy of 240kJ. Our analysis indicated that most of the energy is concentrated between 5 and 15Hz, with a peak at 10Hz, as shown previously in Figure 6. The velocity is typically 2mm/s, which is above the limit of acceptance for an office building (0.4 mm/s) and significantly greater than that for sensitive equipment (50µm/s or 0.05mm/s).

Energy from the drop test is about 10 times that generated by the shaker table (with a change in velocity factored by the square root of the change in energy), hence a velocity of about 0.7mm/s would be expected without any mitigation in the nearest buildings. This would exceed the criteria for office accommodation, and significantly exceed that for sensitive equipment. A significant inertia base is required to reduce the velocity imparted to the ground, typically 10 times that of the load.

Based on the assumptions regarding the strong wall/floor test conditions, a velocity of about 0.3mm/s was estimated in the nearest buildings. This would comply with the criteria for office buildings, but exceed that for sensitive equipment. Allowance for the inertia of the strong floor mass has not been included in the calculations as the design had not developed sufficiently. The typical construction shown in Figure 7 below will likely provide adequate inertia to provide a necessary reduction in ground velocity alongside the structure.

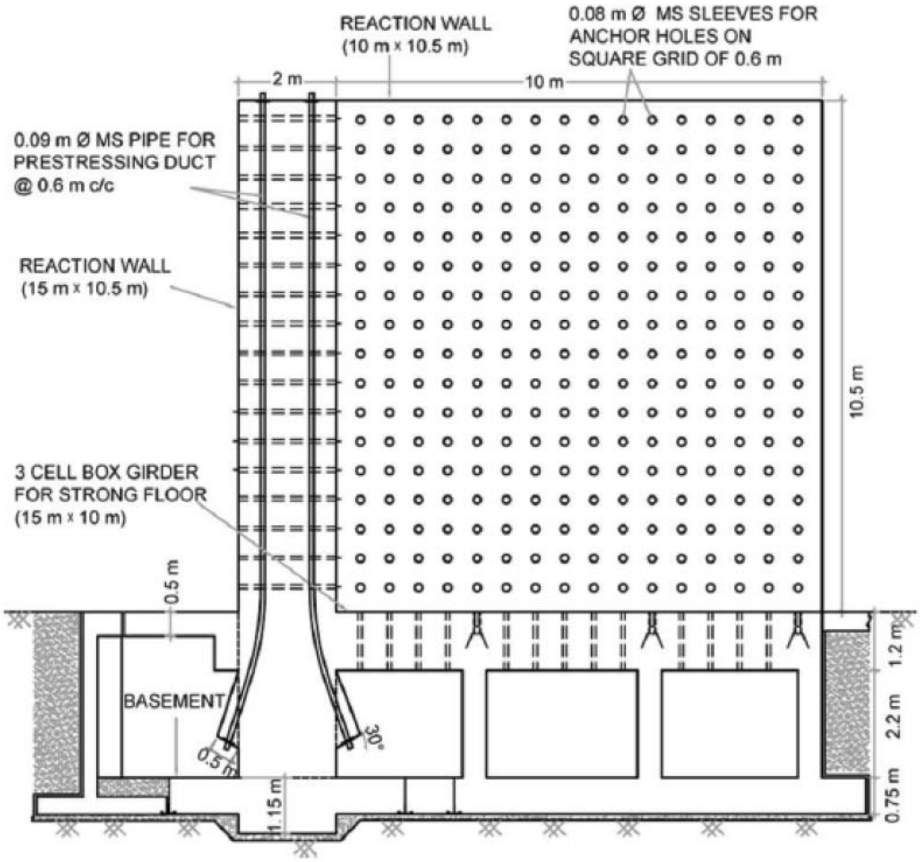

Figure 7 Typical section through the strong wall/floor

Results of our preliminary analysis indicated that a concrete inertia block and anti-vibration isolation matting will be required as minimum treatments to minimise vibration from the SEL. Figure 8 below illustrate the typical isolation required.

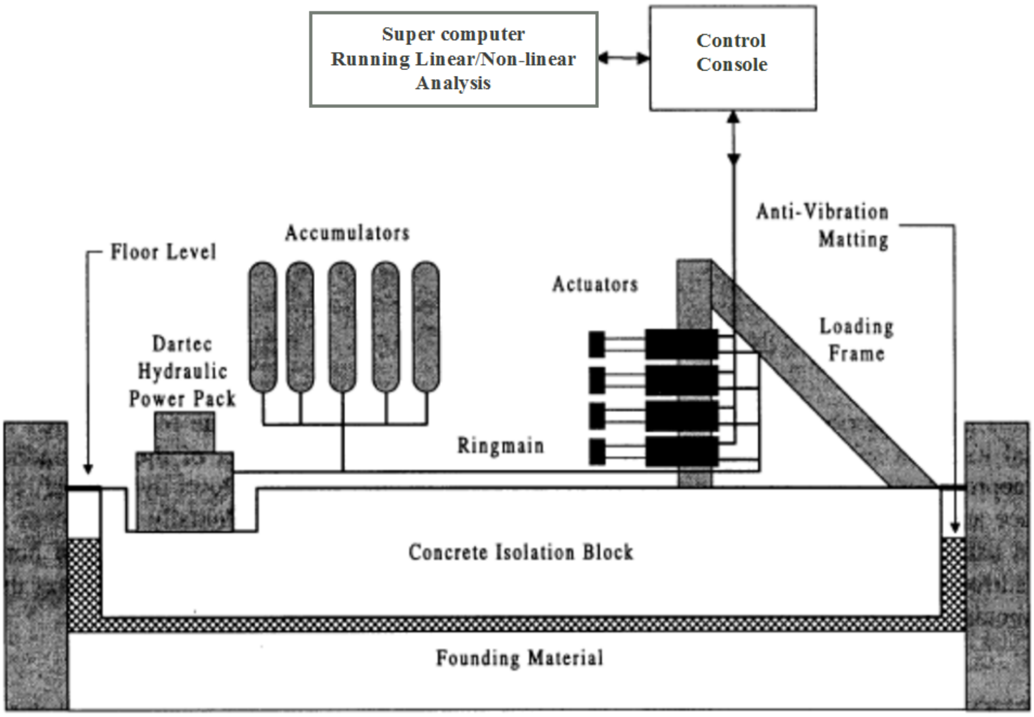

Figure 8 Isolation Requirements

8. Conclusions

Vibration from the testing activities of the proposed seismic test facilities may potentially cause damage to the adjacent structures as well as complaints to the occupants of nearby buildings. To reduce the vibration impact, this paper summarised the study that has been conducted as part of the early stage of the development.

Propagation and attenuation characteristics of vibrations at the project site were investigated. Geophysical technique MASW testing and Impulse Response testing have been undertaken across the project site to understand the behaviour of the soil-structure system response.

The amount of energy imparted by that of the impulse response test relative to the energy-induced by the shaker table and the proposed large scale quasi-static, pseudo-dynamic or hybrid tests has been taken into consideration in our analysis to predict the likely vibration levels at the footings and within adjoining buildings. Computational modelling of dynamic loads imparted into the soil was also carried out to simulate wave propagation in layered media.

Results of the study suggested that reduction in ground vibration from the proposed test facilities can be achieved by installation of an appropriate concrete inertia block and anti-vibration isolation matting. The conclusion drawn from this study can be used at an early phase of the development to improve the effectiveness of the SEL building design.

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