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Shaking Gordon Wilson Flats: early seismic engineering research in New Zealand

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In the late 1950s and early 1960s, Gordon Wilson Memorial Flats (Wellington, New Zealand, 1955–1959) was instrumented for seismic engineering research and subjected to vibration testing. The research was prompted by new thinking about architectural design in the mid-twentieth century (i.e. modernism) that had caused a mismatch between structural assumptions in building codes (which relied on significant amounts of uncalculated stiffness inherent in 1920s building design) and the structural characteristics of new buildings that had, for example, greater areas of glazing. This type of research led to the revision of New Zealand building codes in the 1960s and informed Japanese processes for permitting buildings higher than 100 ft (30·5 m). This paper outlines the research conducted and provides the context for understanding its significance. It is particularly topical given current proposals to instrument 400 Wellington buildings, creating the highest density of seismic instrumentation in any city.

1. Introduction

The recent proposal to install accelerometers in Central Business District buildings in New Zealand's (NZ) capital city to 'provide immediate feedback on … how much shaking a building has endured in an earthquake' (Cann, 2017) is by no means a new one. This paper documents the role that one Wellington building, the Gordon Wilson Memorial Flats (GWF), played in NZ's first research project installing accelerometers in buildings, beginning approximately 60 years ago. GWF was NZ's first fully instrumented building and an early, if not the first, NZ building 'shaken' in forced-vibration testing. That research aimed to measure and record the building's performance in seismic conditions, specifically to

- compare engineering calculations and computations with measured performance
- identify vulnerabilities in buildings
- improve the design of buildings
- inform building code standards.

This paper begins with a brief description of GWF before discussing research undertaken in the building. The paper concludes by discussing the broader architectural historical significance of GWF's role in NZ's seismic research history.

2. GWF

GWF (1955–1959) is a post-war modernist building (Figures 1 and 2). It is the last high-rise state housing block to be built in NZ, and, with the proposed demolition of Auckland's Upper Greys Avenue Flats, it will be the only NZ post-war high-rise state housing block. The building was a product of the innovative and progressive era of state architecture associated with government architect Gordon Wilson, who died as the building was completed, causing its renaming – to memorialise Wilson – from The Terrace Flats to Gordon Wilson Memorial Flats. GWF is recognised in the Wellington City Council District Plan heritage schedule, and its significance was recently confirmed in the Environment Court (*Architectural Centre* v. *Wellington City Council* [2017]). While it is known that seismic research occurred in the building, the details and significance have not been examined by architectural historians to date.

3. The request to instrument GWF

NZ's formal engineering seismology research programme began at the Department of Scientific and Industrial Research (DSIR) in the 1930s, but was interrupted by World War II (WWII) (Galbreath, 1998). Prompted by an Institute of Engineers' 'request for … a programme of research into the ground motions of the destructive phases of earthquakes which would provide information of engineering value' (Murphy, 1956: p. 21-1), the DSIR restarted 'research in engineering seismology' in 1948 under J. B. C. Taylor at the Dominion Physical Laboratory (DPL) (Galbreath, 1998; Murphy, 1956; Taylor, 1951a). An Advisory Committee of 'Engineers, Architects and Seismologists … to assist in formulating, the proposed programme' was also formed (Murphy, 1956: p. 21-1).

It is within this context that the NZ Commissioner of Works wrote to the managing director of the State Advances Corporation, stating that the DSIR

> is engaged in installing a number of acceleragraphs [sic] … to record ground motion in the event of heavy earthquake shocks.… The multi-storey flat building [GWF] is an ideal type for this purpose as it is tall, slender and symmetrical and is located in an active seismic area.… I should be pleased to have your approval in principle to the installation of this equipment so that officers of the Department of Scientific and Industrial Research can proceed with detailed design.… The matter is urgent, as it is anticipated that piling will commence in a few weeks and that subsequent progress will be reasonably rapid. (Hanson, 1955)

The building is located perpendicular to former small streams – that are now a mix of clays and silts – between two rock outcrops. This has resulted in asymmetrical foundations with

Figure 1. GWF and neighbouring houses (4 February 1958). Source: *Dominion Post* Collection, Alexander Turnbull Library, National Library, Wellington, NZ. Reference: EP-Industry-Housing-State-02

Figure 2. GWF under construction (14 November 1957). Source: *Evening Post* Collection, Alexander Turnbull Library, National Library, Wellington, NZ. Reference: EP/1957/4364-1-F

piles, ranging from 48 ft (14·6 m) long in the centre down to 20 ft (6·10 m) long at the two ends of the building (Anon, 1961). The interest in GWF as a ten-storey, 100 ft (30·5 m) high block of flats for instrumentation was stated to be because the building was ‘tall, slender and symmetrical and … located in an active seismic area’ (Hanson, 1955). Additionally, the 1959 annual report by DSIR (1960: p. 34) identified the importance of research on post-war buildings, specifically due to the introduction of shear walls

> it is important that their dynamic response to earthquakes should be thoroughly understood, particularly as architectural design is falling so closely into step with functional engineering design that the lessons learned from the performance of the conventional building of 20 years ago in an earthquake are no longer directly applicable.

The impact of significant changes in architectural design, rendering earlier research findings less relevant, was also recognised internationally, with Ewing and Herd (1956: pp. 35–36) observing that

> [t]he type of building available for study following the Long Beach and Santa Barbara earthquakes, and which greatly influenced the thinking of the engineering profession, was a building having large wall areas, comparatively small windows and a large reserve of uncalculated stiffness and strength. The building of today, on the other hand, contains large glass areas with a correspondingly very small reserve of uncalculated stiffness. … We are now dealing with an entirely different kind of a building.

Consequently, as a post-war shear wall structure, with larger areas of glazing than pre-WWII high-rises, GWF was a highly relevant structure to investigate, particularly as laboratory tests were considered insufficient for understanding shear wall structures (Skinner *et al*., 1971).

The interest in GWF was also possibly related to a DPL project developing ‘an electrical analogue of a building up to 10 stories’, which reproduced ‘the dynamic characteristics of an accelerograph record of an actual earthquake’ (Murphy, 1956: pp. 21–27). The use of electric analogues for seismic research dates from the late 1940s. Housner and McCann (1949) reported on the Electric Analog Computer (EAC) at the California Institute of Technology, identifying its benefits as reducing computation time by a factor of 30 or more over the torsion-pendulum analyser made in 1940 and the ease of analysing multiple-degrees-of-freedom structure. Electrical analogues were versatile and convenient to use and enabled precise control over damping, and it was easy to record measurements from them (Bycroft, 1960; Housner *et al*., 1953). Housner and McCann (1949: p. 56) found that the accuracy of the EAC to be ‘well within the limits of accuracy required … [and] equally reliable over the entire range of periods’, while Housner *et al*. (1953) used accelerograms of 14 earthquakes, supplied by the US Coast and Geodetic Survey (USC&GS), to compute spectra and found that the EAC enabled precise control over damping. They concluded it to be ‘the most satisfactory means at present available for spectrum analysis’ (Housner *et al*., 1953: p. 119). The electric analogue was used in the same way that mechanical models have been used previously, to analyse an acceleration record or compute the seismic response of a building using accelerographs from earlier earthquakes, often the 1940 El Centro (CA, USA) earthquake. During their development, comparison and calibration with physical tests on full-sized buildings, such as what would happen at GWF, also occurred.

The DPL analogue was completed in 1955 and enabled faster analysis than manual calculations. An explicit connection with the GWF instrumentation and the analogue was made by Murphy (1956), and the completion date of 1955 coincides with the Commissioner of Works' request quoted earlier, suggesting that the GWF instrumentation would enable measurements from the building to be compared with results from the analogue.

The analogue tested three ten-storey ideal structures (the uniform type, the graded type and an intermediate type) against recorded spectra of historic earthquakes to generate response curves and enabled the seismic response of an 'equivalent ten-storey building' to be calculated for any building of *N* storeys (Murphy *et al*., 1956a; Skinner *et al*., 1960; Tung and Newmark, 1955). The data from the analogue were used to produce a handbook for architects and engineers, which included graphs of standardised response spectra, later known as Skinner curves (Skinner, 1964; Skinner *et al*., 1960). Ten storeys corresponded to NZ's 100 ft (30·5 m) building height limit (Murphy *et al*., 1956b), and this modelling, informed by international work, led to the 1965 revision of the seismic provisions for a revised New Zealand Standard Model Building Bylaw and the lifting of the 100 ft height restriction (Galbreath, 1998: p. 213). According to Hisada, the 1921 Japanese Building Code also had a 100 ft (30·5 m) building height limit in commercial zones. This code was repealed in 1964 following 3 years of research (Hisada, 1968; Muto, 1965; Otsuki, 1956).

The decision to instrument GWF was thus integral to the building's physical design as a ten-storey, post-war, modernist building. Its location in seismically active Wellington increased the likelihood of recording microtremors and earthquakes, and its government ownership no doubt reduced barriers associated with gaining permission to conduct seismic tests on buildings (Nielsen, 1964). Additionally, the building was seismically aware, Johnston (1960: p. 465 identifying the use of timber floors and partitions within the two-storey maisonette unit to reduce weight, and the staggered openings in the longitudinal spine wall, which enabled the depth of the building to permit 'effective horizontal reinforcement', as specific seismic design.

3.1 Strain gauges

GWF's instrumentation included strain gauges embedded in its structure. These were developed in the early 1950s by the DPL 'for measuring strain both in the steel and concrete of engineering structures' and to be 'built into a building and used to record strains in structural members when an earthquake occurs' (Taylor, 1951a: p. 436). This work was influenced by research undertaken in California (Taylor, 1951a), possibly the same work reported on by Duke and Brisbane (1955). In 1950–1951, Mark I (variable inductance) strain-gauge capsules were embedded in the concrete in the Otahuhu substation building (DSIR, 1952a, 1952b, 1954, 1955; Taylor and Evans, 1955). This installation appears to have been the first use of strain gauges in an NZ building. Just over 3 years later, readings of the strain gauges were taken, with 15 of the original 17 installed appearing to be 'working satisfactorily' (Taylor and Evans, 1955: p. 260). This research fed into the instrumentation of GWF. By the end of 1956, strain gauges 'on steel and in concrete' had been installed in GWF but instruments for recording acceleration were yet to be developed (DPL, 1957–1970). Johnston (1960: p. 465) described the gauges as being located 'at the lower level', and Skinner (1963: p. 314) stated that they were 'embedded in the concrete'. It is thus likely that the strain gauges are still in the building structure.

3.2 Accelerographs

When the DPL started their development of accelerographs in the early 1950s, few appear to have been designed for seismic engineering purposes, and none was widely commercially available. Accelerographs typically included accelerometers for measuring acceleration, recorders for recording acceleration and supporting apparatus (e.g. a trigger unit, a power source and an amplifier unit). Two-component accelerographs (with two accelerometers) measured perpendicular horizontal acceleration in two directions, and three-component accelerographs also measured vertical acceleration. Halverson's (1965) summary of 'the significant strong motion accelerographs of the various countries' identified

- two USC&GS accelerographs (1932, 1962–1963)
- five Japanese accelerographs (Strong Motion Acceleration Committee (SMAC) 1953 and 1955 and Hosaka Company's Ishimoto accelerograph (DC-3))
- the United Electro Dynamics AR-240 strong-motion accelerograph (1963)
- the *c.* 1964 NZ mechanical-optical (MO1) three-component accelerograph (referred to as super ceding the earlier *c.* 1955 type EB accelerograph)
- an undated Union of Soviet Socialist Republics 's UAR accelerograph.

The first NZ accelerograph (type EB) was near contemporary with the Japanese 1953 development of the SMAC accelerographs (Duflou and Skinner, 1965; Taylor and Harrison, 1955). The need for its development was due to the cost of importing instruments. The DPL accelerograph comprised a cabinet (containing a commercially available recorder, a battery charger and an amplifier) and a ground unit (with two simple mass-on-spring accelerometers at right angles and the trigger unit). It was powered by mains electricity with an automatic battery backup and was 'put into service at the Laboratory in April, 1954' (Taylor and Harrison, 1955: p. 186).

It is not completely clear which accelerographs were used in GWF because several instruments were being developed simultaneously and project statements do not always identify specific instruments, although Bill Stephenson, who worked with Ivan Skinner, recalls that

Figure 3. Location of spaces with accelerometers (A, B and C) and recording instruments (D), GWF east elevation. Each of the 15 units on a floor is 12′8″ (3·9 m) wide. Source (architectural drawing): Wellington City Archives

the accelerometers recorded ‘on heat-sensitive paper’ and were ‘powered by a car battery on float charge’ (G. McVerry, personal communication (e-mail), 9 June 2017). Hanson (1956) outlined the proposal for installation (Figure 3) as follows

> It is now proposed to locate all the recording equipment in the triangular void under the bottom flight of the north stairway [Figure 3, position D]. However, it is desired to locate measuring equipment in three flats in bay No. 8 [Figure 3, positions A, B and C]. This equipment would be contained in sealed boxes 12″ square by about 3″ deep, which would be bolted to the concrete ceilings above the second, sixth and tenth floors, in identical positions above the internal staircases. This equipment would be wired electrically to the recording equipment under the north stairway.

By the end of May 1959, 12 accelerometers had been installed, with the imported Century Recorder being installed by November 1959. The instrumentation of the building was ‘[c]omplete, installed, and … working’ by May the following year (DPL, 1957–1970). The November 1960 DPL project statement summarised this instrumentation as ‘a range of field seismographs and … motion and force recorders’ (DPL, 1957–1970).

The instrumentation of GWF was generally successful. Skinner *et al.* (1971: p. 33) reported that ‘[t]he building normal modes and periods were measured with a building shaker and the measured earthquake responses have been consistent with this measured dynamic character of the building’. The records of the building’s response to actual earthquakes included ‘[a]n interesting record’ from a small shake in early 1961 and recordings of the 1962 Westport earthquakes, one of which showed ‘an unusually high frequency component compared to overseas records’ (DPL, 1957–1970, 1960–1965). Adams and Le Fort (1963: p. 508) note more generally, with respect to the Westport recordings, that the recordings ‘yielded much useful seismological information’. These NZ-specific data were significant because, as Murphy (1952: p. 232) wrote, ‘[w]e cannot “adopt” curves of intensity of seismic disturbances from other countries any more than we can adopt curves of rainfall, wind or tidal action from abroad’. The GWF was still instrumented in 1971 with five interconnected accelerographs (Skinner *et al.*, 1971).

3.3 Forced vibration

Following the instrumentation of GWF, forced-vibration tests (where the building is shaken by a building vibrator and then its response is measured) were carried out in early 1964. Historically, such research focused on observing a building’s natural period as an indication of stiffness. The identification of the resonant frequency, when ‘the amplitude of the building-vibration becomes maximum’, identified when and how the greatest damage to a building would occur and thus the mitigation needed to prevent structural failure (Takeuchi, 1960: p. 961). Vibrators were developed because other sources of building vibrations (e.g. wind, traffic and earthquakes) had numerous disadvantages, including the inability to control the force (in terms of time of occurrence, magnitude and spatial distribution and to duplicate tests) and the difficulty of separating ‘the effects of the individual modes of vibration in a complicated structure’ (Hudson, 1961: p. 1; Keightley, 1964).

Prior to the GWF vibration tests, Hudson (1961) identified the following building vibrators

- the 1934 USC&GS shaking machine (Figure 4)
- a second USC&GS shaking machine (Figure 5)
- the *c.* 1948–1951 Japanese Committee for Seismic Tests of Structures (CSTS) building vibrator
- the *c.* 1961 California State Division of Architecture building vibrator.

These building vibrators are referred to in order to provide an international context for the historical development of NZ machines

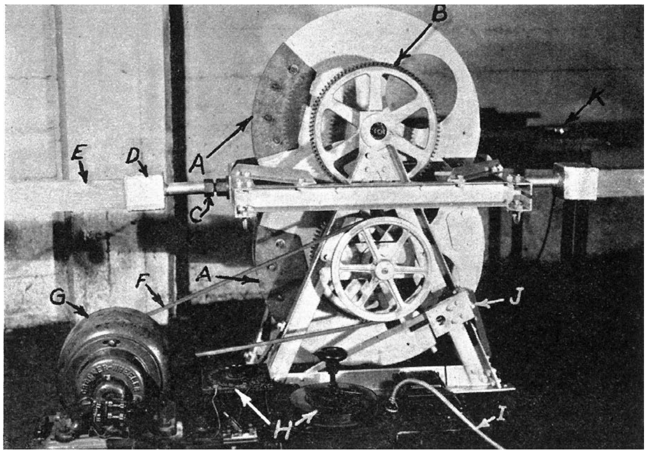

Figure 4. USC&GS shaking machine (1935). Source: Blume (1935), Figure 2

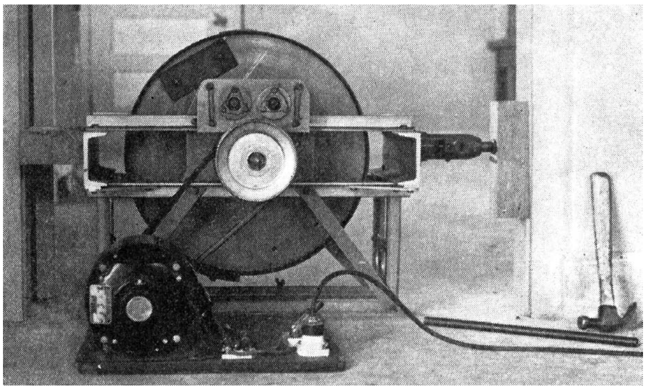

Figure 5. Second USC&GS vibrating machine. Source: Macelwane (1947), Figure 179

and the use of the second DPL vibrator that was used in GWF (Figure 7). The DPL built a building vibrator in 1949, contemporary with the Japanese CSTS shaking machine (Taylor, 1951a). This vibrator was intended as a ground vibrator, but it could also be used for buildings. It was based on the machine built by the USC&GS, which the DPL was in close contact with, and a copy of the DPL report on the NZ machine was distributed to the USC&GS (Taylor, 1949, 1951b). The vibrator produced a maximum force of 3400 pounds (1542 kg) with a maximum speed of 900 revolutions/min (Murphy, 1956; Taylor, 1949, 1951b) (Figure 6). Taylor (1949) identified the main difference between the NZ and USC&GS machines to be the mechanical design. The NZ designers used whirling arms (rather than wheels), rotating around a single axial, to carry the out-of-balance weights. This reduced the weight of the machine and increased portability.

The 1949 vibrator appears to have been the shaking machine which Galbreath (1998) identified as intended to vibrate the Wellington East Post Office (1930) on 21 August 1951 (Taylor, 1951a). The post office had housed the DSIR Radio Development Laboratory during the war (1941–1945), making its choice as test subject unsurprising (Anon, 1945). It had been designed by the government architect under the Model Building Bylaw and was almost the maximum building height of 100 ft (30·5 m) (Galbreath, 1998; Kernohan, 1994). In the end, the shaking machine was not used because the ‘vibrations set up by traffic and wind were sufficient for the measurements’ (Galbreath, 1998: p. 212; Taylor, 1952).

A decade later, Skinner (1963) referred to the construction of another shaking machine. In early 1964, it was used to vibrate GWF. Photographs of the two machines show different machine proportions and size of unbalanced weights, but the USC&GS concept and use of rotating arms, rather than wheels, is constant (Anon, 1964; Taylor, 1949) (Figures 6 and 7). The first tests were postponed because ‘a woman tenant complained about the noise’, but it is clear that the tests were undertaken and useful results were obtained (Anon, 1964: p. 1; Thompson, 1964).

A September 1965 letter to Dr Hisada, Building Research Institute, Ministry of Construction, Tokyo, from C. F. Candy, designing engineer, provides greater details of the results of the vibration tests and that Hisada had written in August, specifically requesting information on the GWF tests. Candy (1965) briefly described the building, including subsoil conditions, and its structure as a ‘cellular form’, with a longitudinal ‘internal “spine” wall’, built of ‘concrete and intermediate floors in timber’. He identified the ‘vertical position of the lift …. [as having] a considerable effect on the buildings [sic] response’ (Candy, 1965) and referred to Skinner *et al.*’s (1965) ‘Unbalanced buildings’ conference paper as including results from the GWF vibration tests. This paper noted that ‘[t]he building was of balanced design, but it was evident that there was some unbalance in the stiffness of the foundations, … [but] the torsional increase is not severe’ (Skinner *et al.*, 1965:

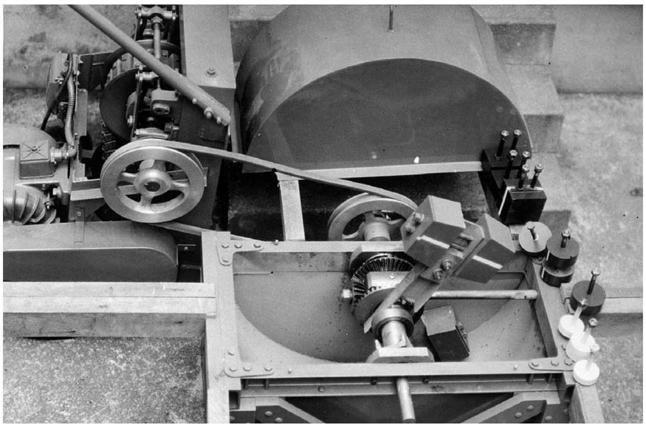

Figure 6. NZ building vibrator built in 1949 based on the USC&GS shaking machine, DPL report number 93. Source: Taylor (1949), Figure 6

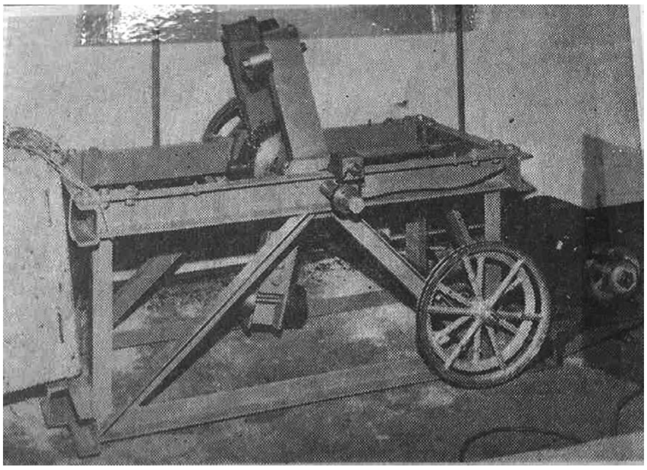

Figure 7. NZ shaking machine used to vibrate GWF in 1964. Source: Anon (1964: p. 1), *Dominion*

p. II-595). The paper's conclusion also pointed to damping in a severe earthquake as being different from that in vibration tests, meaning that vibration tests of buildings with a small unbalance 'will give large torsional effects which increase the difficulties of measurement and analysis' (Skinner *et al*., 1965).

The recipient of Candy's letter, Toshihiko Hisada (1914–1988), was a significant figure in Japanese seismic research and no stranger to NZ when he wrote his August 1965 letter. In the late 1950s and early 1960s, he was associated with a finding (the Hisada effect) that 'better dynamic behavior would be obtained only by designs that take into consideration both strength and stiffness' (Muto, 1965: p. 128). In the late 1960s, he was the director of the Japanese Ministry of Construction's Building Research Institute, the chairman of the High-Rise Building Structure Examination Board and the chairman of the Japan National Committee of Earthquake Engineering (Hisada, 1968). He visited NZ at least twice in the early 1960s. He was invited by the Concrete Masonry Association to visit NZ in March 1963, during which he gave lectures to 'architects in Christchurch', and engineers 'in Dunedin, Wellington, Hamilton and Auckland' (Anon, 1963: p. 109). A government telegraph from the time indicates that Hisada was 'hoping to see some tall buildings in Auckland on Monday 25 March' (Gilkinson, 1963). It is possible that it was this visit that prompted Gilkinson, the Commissioner of Works, to write to Hisada for advice a year later in March 1964. In that letter, Gilkinson (1964) sent notes on 'the possible effects of diagonal cracking on the reinforcing in shear walls', stating that '[t]here does not appear to be any information in the English literature that relates this problem to shear walls'. He asked whether Japanese scientists had carried out relevant tests and indicated that any information would be gratefully received.

Hisada had also attended the Third World Conference on Earthquake Engineering held in NZ in early 1965, where he contributed a co-authored paper on 20-storey buildings (Hisada *et al*., 1965; NZNCEE, 1966). The technical sessions of the conference in Wellington were held at Victoria University, in close proximity to GWF, which was 'higher than other buildings of the time' (NZNCEE, 1966; WCC, 1995). Given this, it is highly likely that most of the conference delegates saw what is still evident today: GWF as a dominant building in its landscape (Figure 1). It was perhaps at the conference then that Hisada first became aware of the GWF, leading to the correspondence the following year. Hisada's interest in the GWF tests was likely related to its 100 ft (30·5 m) height. While NZ was yet to increase the building height limit, Japan had just done so, resulting in the establishment of a High-Rise Building Structure Examination Board of 20 specialists in September 1964 in order to examine '[a]ll buildings over 45 meters in height and those exceeding 31 meters and not designed by the present seismic code' (Hisada, 1968: p. 2). Hisada was no doubt interested in recent seismic research on tall buildings, but undoubtedly particularly those of contemporary design, structurally akin to the new building designs that the board would be required to evaluate.

4. Architectural historical significance

The research presented here demonstrates that GWF was an early instance of an NZ building which was instrumented and subjected to forced-vibration tests for seismic research. While the Otahuhu substation appears to have been the first building in NZ in which strain gauges were installed (1950–1951), the GWF instrumentation was more elaborate, including accelerographs as well as strain gauges. Skinner *et al*.'s (1971) table of instrumented buildings indicates that GWF was the first building in NZ to be comprehensively instrumented, supporting Skinner's (1963: p. 314–315) statement that '[a]t present one Wellington building has been fairly extensively instrumented: a 100 ft high block of flats'. More recent publications summarising NZ's history of instrumentation identify the 1960s with early instrumentation, reporting a gradual build-up since time-based three-component accelerographs were 'placed in the field in 1966' and 'the first array [… being] installed in the Vogel building in Wellington in 1969' (Cousins, 1993: p. 381; McVerry, 1984). Trifunac (2009: p. 602) likewise stated that 'in New Zealand, strong motion measurements started in the mid-1960s'. All of this points to the uniqueness of GWF's instrumentation in the 1950s.

Understanding that GWF was the first NZ building to be instrumented contextualises the importance given to the project by Ward (1959), the DPL director, who stressed the national significance of the GWF instrumentation programme.

> There is no question of the value of the results that can accrue from this very long-term undertaking. The loss to New Zealand from a large earthquake is gigantic. We are using the Terrace flats not to find how the Terrace flats would behave for their own sake but to find how to make all future buildings in New Zealand safe against earthquakes.

A similar primary status appears to be viable for GWF with respect to forced-vibration research. The Wellington East Post Office building is the only earlier building in the NZ literature referred to in relation to forced-vibration tests, but these tests did not eventuate. The building of the second vibrator, specifically for buildings in 1963, and the 1964 forced-vibration testing of GWF, suggest that GWF was one of the first NZ buildings, if not the first, subjected to forced-vibration testing.

NZ was not unique in its lack of instrumented buildings in the 1950s. Trifunac (2009) attributed this internationally to the cost of accelerographs (US$8000 in 1964; NZ$91 580 in 2018). Hudson (1960: p. 1110) refers to 'several buildings in San Francisco, Los Angeles, and Tokyo that are instrumented with sufficient completeness', while Blume and Binder (1960: p. 1195) stated, of multistorey buildings constructed in active seismic areas, that '[a] few of these tall buildings have instruments installed to record building movements during earthquakes'. In 1956, in Japan, only ten accelerographs in six buildings appear to have been installed (Takahasi, 1956). It was after the mid-1950s that Japanese instrumentation increased significantly, and, by 1964, 180 instruments had been installed, with Muto (1965: p. 121) anticipating 'that more than fifty accelerographs will be installed in [the] 1964 fiscal year'. Trifunac (2009) identified 71 stations by 1964 in America, stating that the 1965 ordinance requiring Los Angeles and Beverly Hills owners of new buildings taller than six storeys to install accelerographs prompted the commercial production of accelerographs and a rapid growth in installations.

GWF was instrumented during the period of 1955–1963, which Skinner *et al*. (1971: p. 32) identify as one of early instrumentation in NZ providing 'valuable strong-motion records … [and] field experience', as well as the refinement of early instruments. In 1963, GWF was still a rare instance of building instrumentation in NZ (Beattie *et al*., 2008). During 1966–1971, the MO1 and MO2 three-component accelerograph network was established. The NZ MO2 accelerograph was commercially produced from 1966 and was a significant development internationally because it was 'the first relatively low-cost instrument which could be readily installed in the large numbers necessary for adequate cover' (Hudson, 1977: p. 113). It successfully competed with the American AR-240 accelerograph because of its low cost, prompting the design of the RFT-250 instrument (Brady, 2009).

After GWF, it was 12 years before the next long-term instrumentation of another NZ building in 1968 (Skinner *et al*., 1971). The Inangahua earthquake, from which the first major records from NZ's strong-motion network derive, also occurred in this year (Cousins, 1993). In Wellington, Challenge House was instrumented, followed by Vogel House in 1969 and the general post office Building and Dalmuir House in 1970. GWF was still the only residential building instrumented in NZ in 1971 (Skinner *et al*., 1971). Skinner *et al*. (1971: p. 33) refer to nine instrumented buildings in NZ (and five in Wellington), with eight 'inter-connected to give simultaneous starting and common time marks'. By 1979, another upgrading of the MO2 accelerographs was proposed (Hefford *et al*., 1979). At this date, 59 MO2 accelerographs were installed in 15 buildings across NZ, including the Charles Ferguson Building, Challenge House, Dalmuir House, the Reserve Bank, Rutherford House and the Vogel Building in Wellington. The absence of GWF in the listed buildings suggests that it was no longer being monitored. Twenty-nine new installations were anticipated in seven buildings across the country, including five in Wellington, making a total of 22 buildings. However, when Cousins (1993) reviewed the history of NZ strong-motion recording in 1993, he mentions only 19 buildings with structural arrays. Cousins (1993: p. 386) also reported an intended systematic upgrading of the network, replacing analogue accelerographs with digital models, and installations at two new sites annually prioritising new buildings because 'most of the currently instrumented buildings were constructed in the 1970s'.

Despite this, a decade later, Deam and Cousins (2002: p. 1) still recorded only 19 instrumented buildings in NZ, describing the instruments as 'now old and expensive to maintain'. They referred to an Institute of Geological and Nuclear Sciences Ltd GeoNet project to extend the building monitoring programme and include a greater range of buildings with modern instrumentation. Five years later, Uma (2007) also reported on the GeoNet programme, referring to 30 instrumented structures – which may have included structures, such as dam and bridges, in addition to buildings – and the intention to instrument a further 30 buildings. Uma *et al*. (2011: p. 56) reiterate this 4 years later, stating that, in 2001 16 buildings (including three base-isolated buildings) were instrumented and that the buildings had obsolete MO2 recorders and were 'mostly non-operative'. They reported that a new instrumentation programme had started in 2006, including five buildings with completed instrumentation in the Wellington region. The current ambition to install accelerometers in 400 commercial buildings in Wellington can thus be linked to the GWF instrumentation, but is also a significant quantitative advance (Cann, 2017).

To provide a more precise international context for the GWF research, a review of literature (using database searches, ancestry searches and a review of the proceedings of the World Conference on Earthquake Engineering) was undertaken and identified buildings which were instrumented and subjected to forced-vibration testing. Table 1 attempts to identify buildings which were instrumented for seismic engineering, rather than geophysical, research (i.e. for understanding building performance rather than ground motion). Generally, terminology ('strong-motion accelerograph' against 'strong-motion seismograph') and the tendency to use multiple accelerographs on different floors in a building distinguish these sites for seismic engineering research, but there is some overlap in description. For example, Ulrich (1936) lists locations used to record ground motion (e.g. Golden Gate Park) in the same table as buildings instrumented to understand building performance (e.g. the Alexander Building). It is also difficult to distinguish sites of long-term instrumentation (e.g. for a decade) from those buildings instrumented for a few months in order to measure microtremors. Table 2 lists buildings subjected to forced vibration.

As a group, the buildings subjected to vibration testing are highly varied. In reviewing the tables, WWII is an important reference point. This is because these structural changes in modern architecture following WWII meant that much pre-WWII seismic research was less relevant to new buildings. Tall commercial buildings, including those made of riveted steel frames and of reinforced concrete, had been subjected to forced-vibration tests in California during the interwar period. A substantial difference between these buildings and GWF is the degree of glazing, reducing building stiffness. However, much of the post-WWII testing involved structures of four or fewer storeys, including schools, apartments and the two-storey test structures of Hisada and Nakagawa's research. The idiosyncratic nature of the buildings selected is likely to be derived from the research context, driven by either regulation and research funding – such as the Californian school research – or the cost of testing of full-scale structures. Access to full-sized structures is frequently opportunistic, rather than meeting narrower research agenda (e.g. the testing of the Encino

Table 1. Instrumented buildings prior to GWF

Date of installation	Building	Location	Building type	Reference
1926 1929/1930	Marunouchi Building	Tokyo	Retail and office building	Trifunac (2009) Fukutomi (1934)
1929/1930	Earthquake Research Institute	Tokyo	Research	Trifunac (2009)
1929/1930	Yurakukan Building	Tokyo	Office building	Trifunac (2009) Fukutomi (1934)
c. 1931	Takeda Building, Nihon-basi St			Fukutomi (1931) Fukutomi (1934)
1932	Wooden European-style building	Tokyo		Fukutomi (1934)
1932	Four wooden buildings, Seismological Institute, Tokyo Imperial University	Tokyo	Education	Fukutomi (1934)
1932	Vernon Central Manufacturing District Terminal Building	Vernon	Transport, warehouse	Trifunac (2009)
1932–1934	Hollywood Storage Building[a]	Long Beach	Warehouse	Ulrich (1936) White (1960)
1932	Public Utilities Building	Long Beach	Civic	Ulrich (1936) Trifunac (2009)
1932 1934	S. P. Building	San Francisco	Office building	Ulrich (1936)
1932 1934	Los Angeles Subway Terminal Building[a]	Los Angeles	Transport	Ulrich (1936) White (1960) Trifunac (2009)
1932	Bank of America[a]	San Jose	Office building	Ulrich (1936) Blume (1935)
1933–1934	Chamber of Commerce	Los Angeles	Office building	Ulrich (1936)
1933–1934	City Hall	Oakland	Civic	Ulrich (1936)
1933–1934	Shell Building	San Francisco	Office building	Ulrich (1936)
1934	450 Sutter	San Francisco	Office building	Ulrich (1936)
1934–1935	Alexander Building[a]	San Francisco	Office building	Ulrich (1936)
1939–1945	**World War II**			
1949–1952	Engineering Building (Unit B), University of California	Los Angeles	Education/research	Duke and Brisbane (1955)
1952	Akashi Seisakusho Co. Ltd	Shinagawa Ward, Tokyo	Manufacturer (accelerographs)	Halverson (1965) Takahasi (1956)
1953–1955	Tokyo Metropolis Residential Association 46-type apartments[a]	Tokyo	Residential	Kawasumi and Kanai (1956) Kanai *et al.* (1956)
1953	Osaka First Life Insurance Building	Osaka	Office building	Takahasi (1956)
1954	Earthquake Research Institute[a]	Tokyo	Research	Takahasi (1956) Kanai and Suzuki (1955) Kawasumi and Kanai (1956) Okawa *et al.* (2004)
1954	Nagoya Culture Center	Nagoya	Civic	Takahasi (1956)
1954	Daimaru Department Store	Chiyoda Ward, Tokyo	Retail	Takahasi (1956)
1955	Tokyo Department Store	Shibuya Ward, Tokyo	Retail	Takahasi (1956)
c. 1955	Nikkatsu (International) Building, Hibiya	Hibiya	(Office building)	Kawasumi and Kanai (1956)
1955–1959	Gordon Wilson Memorial Flats[a]	Wellington	Residential	
Late 1950s	Research Institute of Building Material Building, Tokyo Institute of Technology	Tokyo	Education/research	Kobayashi (1960)
Late 1950s	Office building, Ginza	Tokyo	Office building	Kobayashi (1960)
Late 1950s	Office and apartment building, Nampeidai	Tokyo	Office and apartment building	Kobayashi (1960)
c. 1959	Tokyo Tower	Tokyo	Radio and television tower	Naito (1960)
c. 1960	Six-storey building	Tokyo		Muto (1965)
c. 1964	Four-storey apartment building	Niigata	Residential	Muto (1965)
c. 1964	Akita Prefectural Government Building	Akita	Civic	Muto (1965)

[a] Also subjected to forced-vibration tests

Table 2. Buildings subjected to forced-vibration tests prior to GWF

Date	Building	Location	Building type	Reference
1934–1935	Palo Alto Transfer and Storage Company Building	Palo Alto	Warehouse	Blume (1935)
1934–1935	Los Angeles City Hall	Los Angeles	Civic	Blume (1935)
1934–1935	Bank of America Building[a]	San Jose	Office building	Blume (1935)
1935	Hills Brothers' warehouse	San Francisco	Warehouse	Blume (1935)
1935	Alexander Building[a]	San Francisco	Office building	Blume (1956)
c. 1939	Los Angeles Subway Terminal[a]	Los Angeles	Transport	White (1960)
c. 1939	Hollywood Storage Building[a]	Los Angeles	Warehouse	White (1960)
1939–1945	**World War II**			
1948–1950	Jane K. Sather Campanile	Berkeley	Bell tower	Cloud *et al.* (1952)
c. 1946–1955	Buildings damaged by fires in WWII	Japan		Kawasumi and Kanai (1956)
1951	447 Commercial St	Los Angeles	Warehouse	Alford and Housner (1953)
1953–1955	Tokyo Metropolis Residential Association 46-type apartments[a]	Tokyo	Residential	Kanai *et al.* (1956) Kawasumi and Kanai (1956)
c. 1954	Fuse Middle School	Osaka Prefecture	Education	Kawasumi and Kanai (1956)
c. 1954	Shiratori Primary School		Education	Kawasumi and Kanai (1956)
c. 1955	Pier, Port of Kobe	Japan	Industrial	Amano *et al.* (1956)
c. 1955	Steel-framed concrete building, Hosei University Building		Research	Kawasumi and Kanai (1956)
c. 1956	Fourteen test structures	Japan	Test structures	Hisada and Nakagawa (1956)
c. 1956	Apartment houses, Hitachi Mine	Ibaraki Prefecture	Residential	Kawasumi and Kanai (1956)
c. 1956	Matsuzakaya Department Store, Ginza St	Tokyo	Retail	Kawasumi and Kanai (1956)
c. 1956	Earthquake Research Institute, Tokyo University[a]	Tokyo	Research	Kawasumi and Kanai (1956)
c. 1958–1960	Fifteen schools	California	Education	Blume and Meehan (1960)
c. 1959	Sixty unnamed buildings	Tokyo and Osaka	Including residential	Takeuchi (1960) Nakagawa (1960)
c. 1960–1961	Concrete intake tower, Encino Dam	Los Angeles	Industrial	Hudson (1961)
c. 1962–1964	Second Encino Dam tower and bridge	Los Angeles	Industrial	Hudson (1962) Keightley (1964)
1964	Gordon Wilson Memorial Flats[a]	Wellington	Residential	
c. 1964	Five-storey building	Southern California		Nielsen (1964)
c. 1964	Nine-storey building	Southern California		Nielsen (1964)
c. 1965	Nine-storey Ohbayashi-gumi Building	Osaka	Office building	Watanabe *et al.* (1965)

[a] Also instrumented

dam tower prior to its demolition), or designed with substitutes to fit within financial resources (e.g. the Hisada and Nakagawa test structures). The testing of the eight four-storey Tokyo Metropolis Residential Association 46-type apartments is the closest parallel to the GWF research, and it is perhaps no coincidence that, like GWF, the Tokyo apartments were provided by a government housing corporation for people to rent. All this points to the significance of testing building responses using electrical (and later digital) analogues, which were faster than manual calculations and cheaper and more convenient than tests in full-scale physical structures.

In contrast to vibration testing, a greater number of buildings had long-term instrumentation prior to WWII. Like vibration testing, the Californian instrumentation of Blume and Ulich (linked to the USC&GS) is a substantial contributor. Japanese researchers are also a significant group. Just as Blume's post-war work on schools supported regulatory requirements, the pre-WWII instrumentation of commercial office buildings may reflect Murphy's (1946: p. 308) observation that 'accelerographs were first successfully employed [*c.* 1934] at the request of engineers and insurance underwriters in California'. The similar prevalence of education buildings is likely linked to the pragmatic ease of using university buildings for research and the requirements of the Field Act and Title 21 for engineering data to support new construction in American schools (Ewing and Herd, 1956). The use of residential buildings for research occurs in the 1950s, perhaps reflecting a post-war increase in apartment dwelling. However, as a high-rise residential building, used for both long-term instrumentation and forced vibration, the GWF appears to be rare, despite new post-war thinking about the importance of planning of cities and concern regarding urban sprawl. These concerns created an interest in high-rise dwellings, located close to public transport and the inner city. As documented earlier, GWF's selection for testing and instrumentation appears to be in part due to its government ownership. The tables hence demonstrate the rarity of high-rise post-WWII residential structures as test subjects and GWF's significance in this regard, additional to its greater levels of glazing area consistent with post-war modern architecture.

5. Conclusion

Mid-twentieth-century modernist architecture is increasingly the subject of heritage and conservation projects. An understanding of the heritage significance of these buildings is important in understanding how, and what aspects of, a building should be conserved. The heritage significance of the seismic engineering research conducted on the GWF consequently relates to

- GWF's status as the first NZ building to be instrumented extensively
- GWF's status as an early building in NZ to be vibrated
- the testing of instruments developed by the DPL in GWF
- the records obtained from the instruments in GWF, including to inform the development of the DPL's electronic analogue, the 1964 handbook and the 1965 revision of the NZ Standard Model Building Bylaw.

As a rare example of a high-rise block of flats being used for seismic engineering research and a rare example of a building used for both long-term instrumentation and forced-vibration testing, GWF is one of the few modernist buildings where both the architectural and engineering design have heritage. The Japanese interest in the results from the GWF forced-vibration tests (indicating the relevance of the research beyond NZ) appears to have resulted from the historical context of building regulations relating to height limits and the significant changes to architectural design post-WWII, reducing the relevance of earlier seismic engineering research for new buildings. While the seismic instrumentation in GWF is no longer maintained and monitored, the current plans to install accelerometers in 400 Wellington buildings, 'making the capital the first city on the planet with such extensive coverage' (Cann, 2017), suggests a continued relevance of this heritage of seismic instrumentation for NZ.

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