DIGITISING AND PROCESSING OF ANALOGUE TSUNAMI RECORDS

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ABSTRACT:

A set of analogue records from two tide stations in Papua New Guinea - Rabaul and Loloho has beem digitised for the first time at AGSO, Canberra. The converted digitised waveforms were used in the analysis of the origins of tsunamis and seiches in the area caused by tectonic and volcanic activity. Spectral characteristics were determined for different sources: earthquakes, volcanoes, and submarine landslides. The dominant periods of seiches were compared with the typical period band of the tsunamis at the coastal stations. These findings will contribute to better understanding of the mechanism for generating tsunamis, their propagation, and the design of protective measures.

Paper No. 11

1. INTRODUCTION

Analogue records from tide stations in the southwest Pacific contain valuable tsunami data [1,2], only a fraction of which have been utilised to date. Collecting these tsunamigrams, converting them from analogue to digital format and processing them will allow a more complex analysis and understanding of tsunamis in the region. For that purpose a set of analogue records from two tide stations in PNG - Rabaul and Loloho - has been digitised for the first time at AGSO, Canberra.

AGSO also maintains an Australian Tsunami Database[3], compiled with the Natural Hazard Research Centre at Macquarie University. In the present form this database contains observational records in the Australian region from individual tsunami events. Adding new entries with digitised waveforms will provide the opportunity for detailed research into the propagation and coastal interaction of tsunamis.

2. METHOD

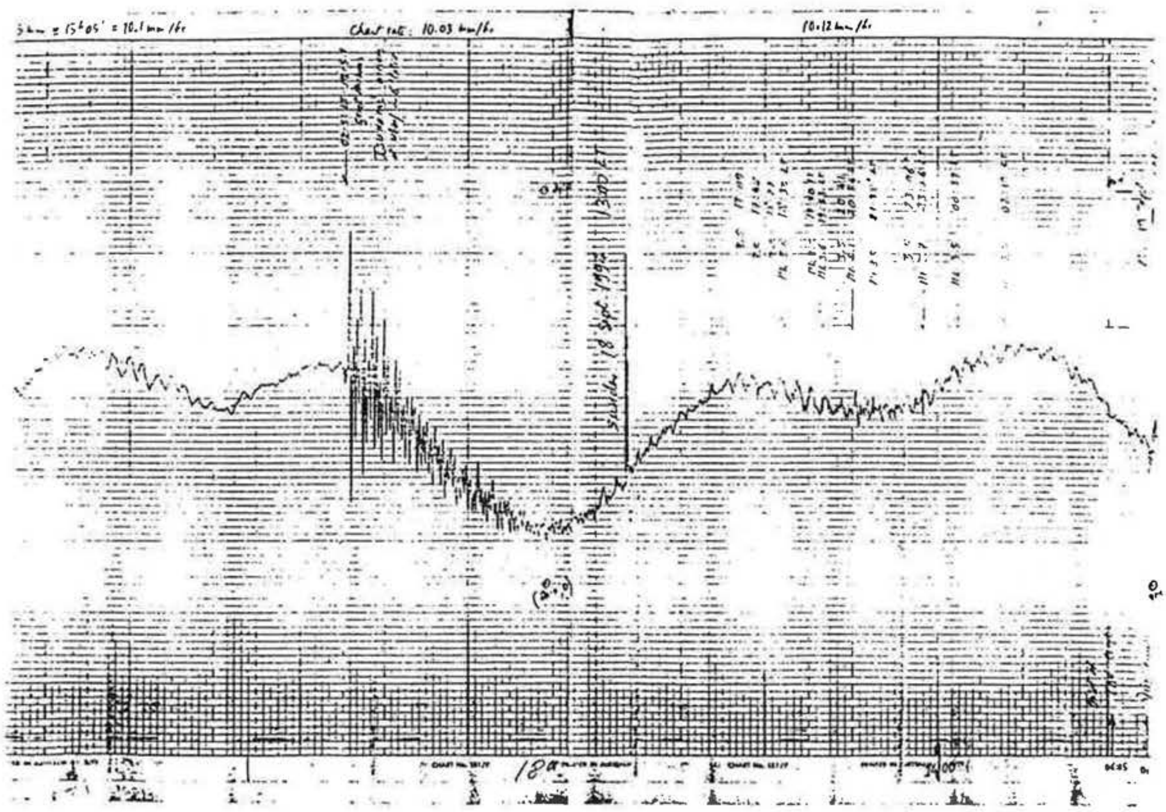
Machine digitisation of analogue records has been practiced for many years throughout the world [4]. In principle, the aim is to digitise in X-Y co-ordinates a sufficient number of points from the analogue trace in such a way that the significant features of the original record can be reproduced between these points by linear interpolation. The objective for tsunami records is to digitise as accurately as possible, following all the fluctuations that can be discretely identified, particularly the highest and the lowest points, and points of inflection.

During the digitisation process in AGSO, the following set-up was used:

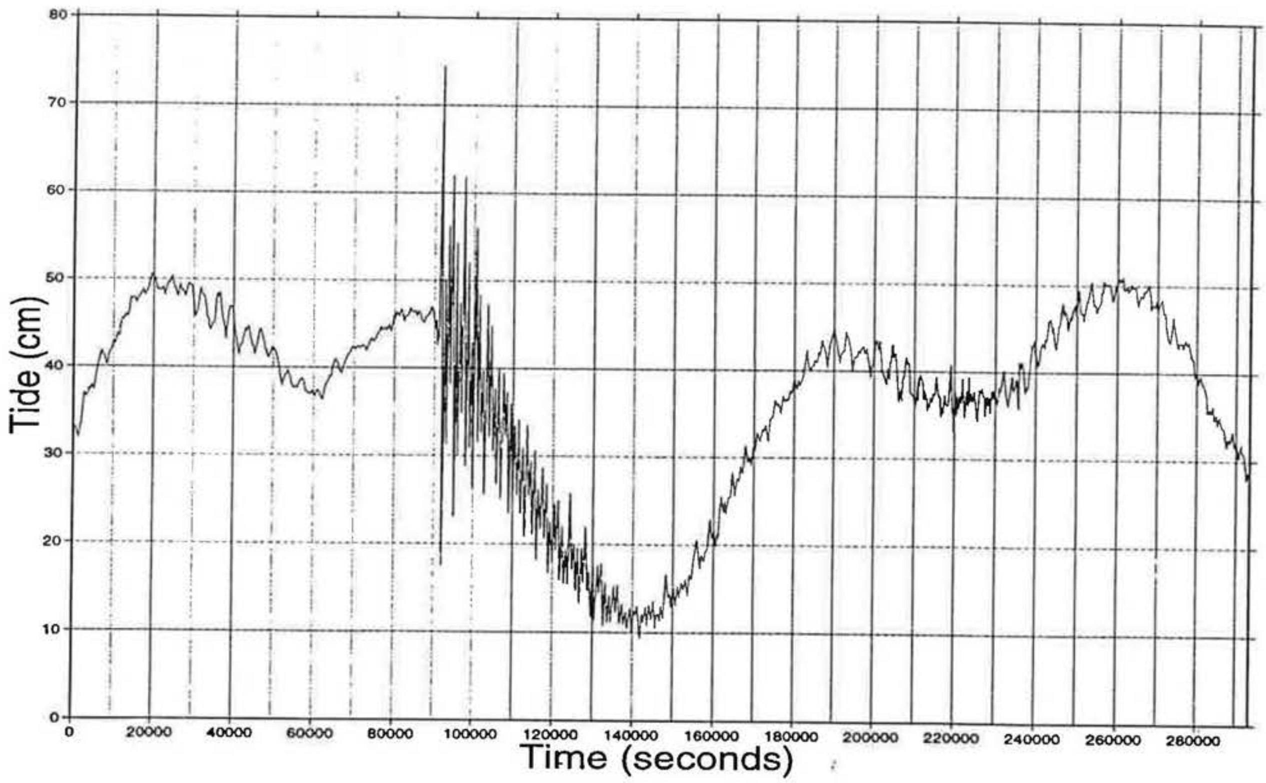
- Macintosh LCIII Apple computer,
- Digitize™ Version 1.50 product of RockWare Inc., Co., USA,
- CalComp Drawing Board II with 45cm x 30cm dimensions, and
- Hand-held transparent cursor with cross-hairs.

Chart records from Stevens A71 tide gauge had one graduation per 15 minutes on the X-axis, and one graduation per 0.05 foot on the perpendicular Y-axis. There were regular time marks on the traces to indicate 24-hours period and ease identification of events. The maximum precision achieved was 70 seconds, which in turn allowed computation down to the Nyquist period of 35 seconds.

Figure 1-a shows an example of an analogue tide gauge record from the instrument positioned at the wharf in Rabaul Harbour. The water disturbance with maximum peak-to-peak amplitude of 50cm originated from a local earthquake M_L=5.1, which occurred on Saturday, 17th of September 1994, at 2:51 UTC. Figure 1-b shows the same record after digitisation; it is noticeable that all the details from the original waveform are well preserved.



a) Analogue record



b) Digital record

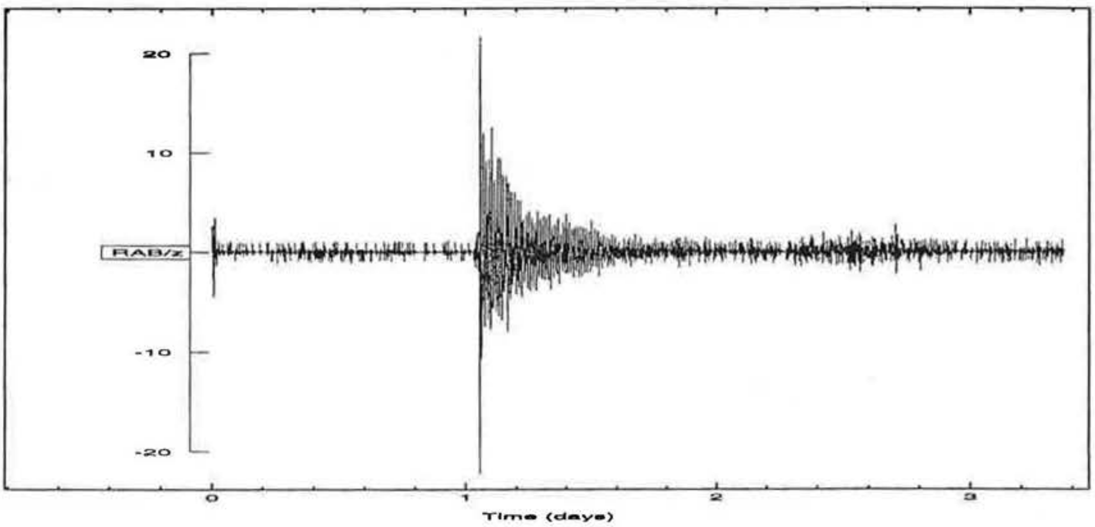
Figure 1: Tsunamigrams of the event of 17 Sep 1994 02:51

3. PROCESSING

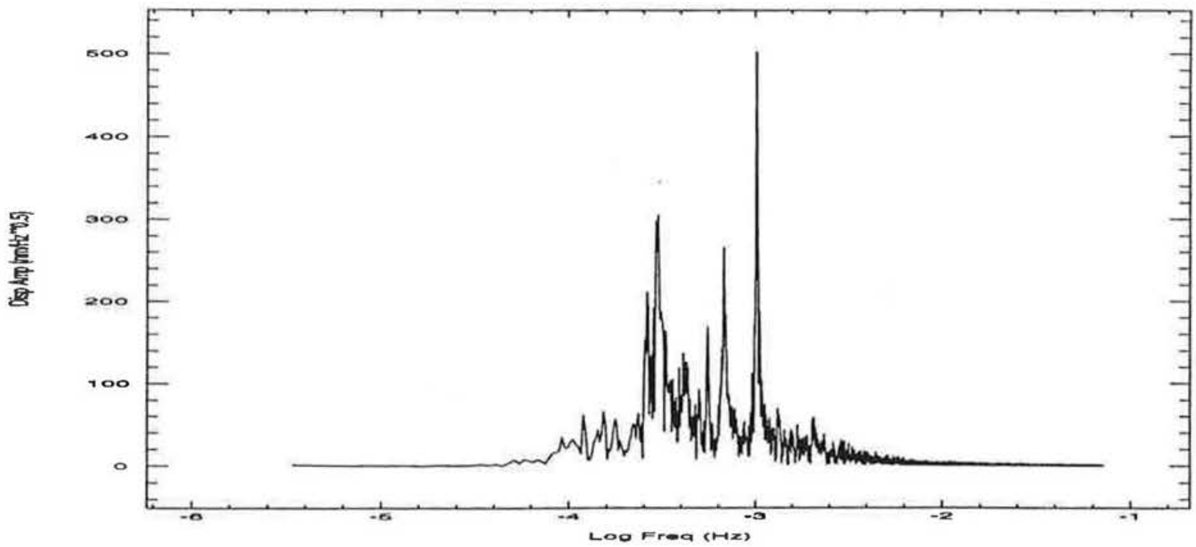
Numerous digitised records from Rabaul and Loloho were further processed on our Unix Sun Sparc workstations using in-house software for data control and correction. Filtering and FFT analysis were performed through geotool™ package product of Data Analysis System, CSS, VA., USA.

To filter out the long period variations, we selected a 4th-order high pass Butterworth filter between 35 and 10,000 seconds, and Hanning taper with 10% overlap. Figure 2-a shows the shape of the waveform from Fig. 1 after filtering; the tsunami arrival is clearly visible.

Figure 2-b shows the result of the FFT analysis of the filtered signal. The most prominent period in this example is around 1000sec or 16.7 minutes.



a) Filtered record



b) FFT

Figure 2: Results of the analysis of the 17 Sep 1994 event

4. RESULTS AND DISCUSSION

Using identical filter setting[5] we found nearly the same values for the dominant period of the FFT analysis of the record produced by the actual volcano eruption in Rabaul, on Monday 19th of September 1994 (Fig. 3). It was apparently caused by successive pyroclastic flows entering the sea at the NE foot of Vulcan. These oscillations of 16.7min are consistent with the observed phenomenon of seiches in the harbour, whose characteristics are determined by the width and depth of the water in the bay.

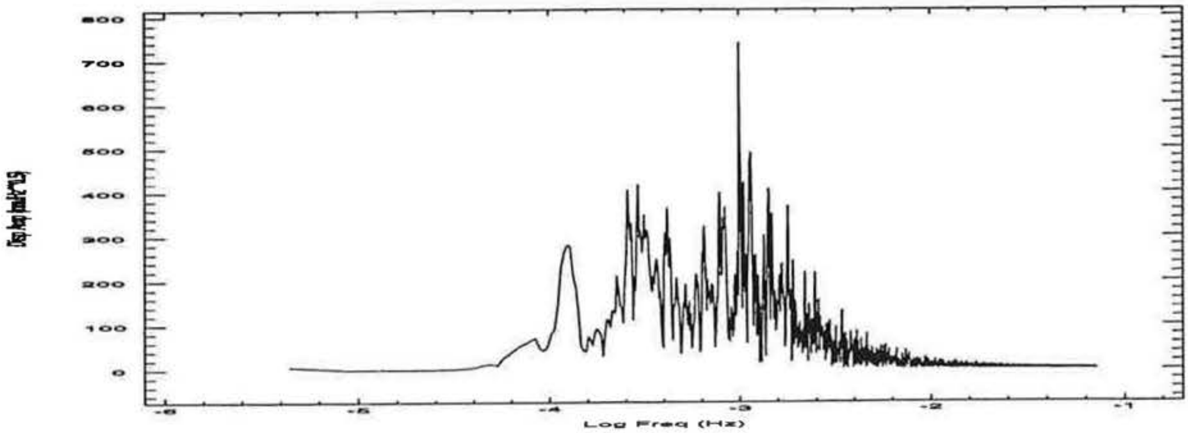


Figure 3: Results of the FFT analysis of the 19 Sep 1994 event

The results of a broader analysis indicated that other dominant periods between 30 to 35min, and around 60min, can be attributed to tsunamis from distant sources, as was previously reported elsewhere[6]. More detailed study including numerical modelling is needed to explain such oscillations. Our objective was to illustrate the present state of tsunami investigations at AGSO, and possibilities for further research with digital data.

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A FACILITY FOR DYNAMIC TESTING AND RESEARCH

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Dr Samali, Associate Professor Faculty of Engineering, joined Maunsell and Partners consulting engineers in 1985 as Senior Structural Engineer and structural dynamics specialist. He joined UTS in 1987. His main research interest is in structural dynamics with emphasis on wind and earthquake engineering. He has published over 100 scholarly papers and has been involved with 26 major projects in a consulting capacity.

Dr Li, Research Fellow in the Civil Engineering Group, has ten years of research experience in fatigue and fracture of materials. Over the past four years Dr Li has led the installation and commissioning of the shaker table at UTS.

ABSTRACT:

The National Facility for Dynamic Testing and Research was recently established at the University of Technology, under a grant provided by the Australian Research Council (ARC) and substantial support from the Faculty of Engineering UTS, the Department of Civil Engineering and the Wind Engineering Services of the University of Sydney, and the Road and Traffic Authority of NSW.

The core component of the experimental testing facility is a shaker table capable of subjecting test specimens of up to ten tonnes in mass to pre-programmed vibrations or, seismic displacements within a wide range of frequencies and amplitudes. This versatile, advanced testing facility can meet the requirements of a wide variety of applications, from testing the performance of products and materials subjected to cyclic loading to the testing of prototype sized structures and components subjected to complex dynamic load/displacement regimes such as simulated earthquakes.

The paper describes the facility which provides investigators a versatile research and development tool in a wide range of areas.

Paper No. 12

1. INTRODUCTION

A National Facility for Dynamic Testing and Research has been established at the Faculty of Engineering of the University of Technology, Sydney. The core component of the Facility is a high performance programmable shaker table which incorporates advanced actuator and control technologies. The acquisition and installation of the shaker table and ancillary facilities were made possible by a research infrastructure grant provided by the Australian Research Council to a consortium comprising the University of Technology, Sydney, the University of Sydney and the Road and Traffic Authority of NSW. This paper describes the features and performance characteristics of the shaker table and the associated control and data analysis software. It also outlines a range of dynamic testing, research and development that will be enabled as a result of the establishment of the National Facility for Dynamic Testing and Research.

2. DYNAMIC TESTING

The need to develop new technologies to minimize the damaging effects of earthquakes, cyclones and other destructive events is widely recognized by authorities with a responsibility for the safety and maintenance of Australia's physical infrastructure. The damage to infrastructure and the disruption to services that can occur in a developed urban community due to such events was illustrated, for example, by the Kobe earthquake of 1995. In Kobe over 5400 people lost their lives and the number of buildings which were demolished or damaged beyond repair is put at 100,000. The disruptive consequences of large scale damage to transport, communication and energy supply infrastructure caused by natural disasters can also have catastrophic effects on a community's ability to maintain basic services. The assessment of the effects of such events on complex structures requires facilities for testing which can realistically simulate the events. The manifest need in Australia for a high performance test and research facility was highlighted by the damage caused by the earthquake at Newcastle and by the frequently recurring tropical coastal storms. The National Facility for Dynamic Testing and Research aims to provide a major educational and research resource to develop the technological and engineering skills of Australia's structural engineers, material scientists and designers. The Facility also provides an unique capacity in Australia to undertake applied research in structural dynamics and earthquake engineering for and in collaboration with industry to underpin the development of new products, technologies and standards. The Facility is being developed to provied a versatile research and development tool in a wide range of areas such as system resonance assessment, control and damping of structural vibrations, facade engineering, dynamic effects of seismic/wind loads and wave action on a variety of prototype sized structures and components.

3. THE SHAKER TABLE

The shaker table and ancillary hydraulic equipment were designed and supplied by MTS Systems Corporation of Minnesota, one of the leading producers of precision dynamic testing equipment. The installation has a 3metre x 3metre table of cellular construction with high natural frequency (~ 85Hz) activated by a uniaxial hydraulic actuator rated for a maximum stroke of ± 100 mm and a maximum force of 150kN. The actuator incorporates a PC based digitally supervised servo controller, function generator and 3-stage stabilized valve driver. Table 1 provides an indicative list of descriptive parameters for the table. Figure 1 shows the performance curves which represent the interaction between frequency, displacement, velocity and acceleration for the performance domain of the table under zero load and also under full load.

Size of table	3 metre x 3 metre
Weight of table	6.5 tonnes
Maximum weight of test specimen	10 tonnes
Maximum displacement	± 100 mm
Maximum velocity	±550 mm/second
Maximum overturning moment	100 kN-metres
Maximum acceleration (with 10 tonne specimen)	±0.9 g
Enabled wave form	Regular / irregular
Range of testing frequencies	0.1Hz to 50 Hz

Table 1: Shaker Table Specifications

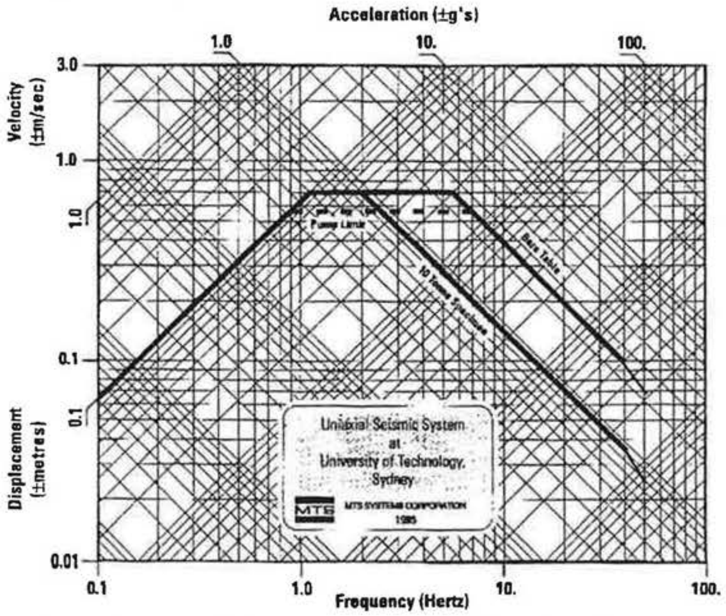

Figure 1: Performance Curves Showing the Performance Domains for Table Subjected to Zero Load and to Full Load

4. CONTROL OF TABLE MOVEMENT

The fidelity with which the movements of the table can be controlled and programmed to comply with a pre-determined wave form is of critical importance in dynamic and seismic testing. Fig. 2 shows an example of the high fidelity between a sine-beat acceleration input signal with a modulating frequency of 1Hz and the response signal measured on the table. The minimization of any spurious displacements of the table in the vertical and transverse directions and of the rotations is of similar importance to effective dynamic testing is. The UTS shaker table has high-quality hydro-static bearings installed on very stiff foundations which effectively restrain all five components of spurious displacements and rotations. Tests were conducted, as part of the commissioning process, to determine the unwanted displacements. Five single frequence sinusoidal signals (described in Table 2) were used to drive the table under displacement control. The table response was recorded by the system accelerometer and five piezoelectric type accelerometers with sensitivities of 100mV/g for triaxial and 1000mV/g for uniaxial gauges. Three triaxial accelerometers were attached to the corners of the table, in addition uniaxial accelerometers, aligned in the direction of excitation, were attached on a longitudinal edge near adjacent corners of the table. The calculated vertical displacements based on the measured data are shown in Fig.3

Type of Signal	Frequency (Hz)	Maximum Amplitude (±mm)
sinusoidal	1	100
sinusoidal	3	31.8
sinusoidal	5	24.8
sinusoidal	10	6.21
sinusoidal	30	0.69

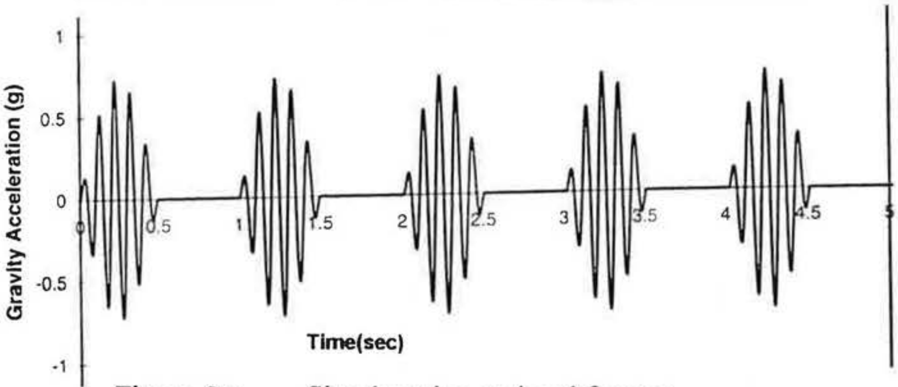

Figure 2a: Sine-beat input signal for test

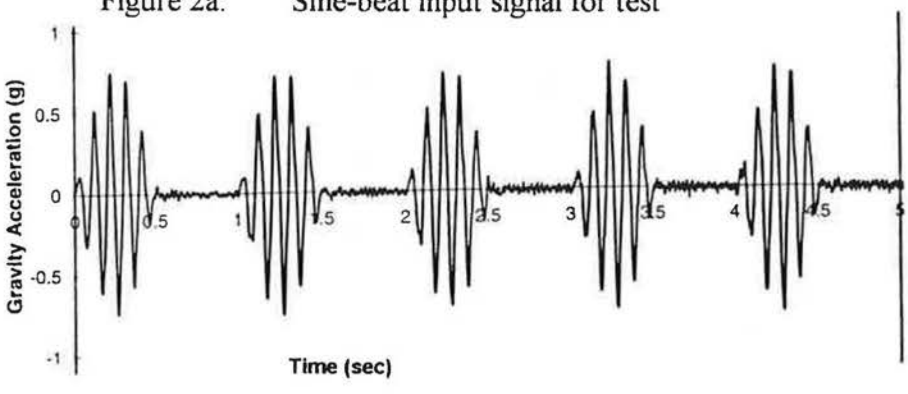

Figure 2b: Measured bare table response

5. INSTRUMENTATION

Effective testing of dynamic response such as the determination of time history acceleration responses at critical locations of a complex test specimen requires high capacity multi channel data acquisition and on-line dynamic signal analysis capability.

The Facility at UTS currently has a work station controlled 36 channel Hewlett Packard VXI data acquisition system. Data logging and advanced dynamic analysis software tools are provided by a CADA-X version 3.4 program suite supplied by LMS International. The Facility is equipped with an extensive range of ancillary equipment which include channel dynamic strain acquisition system, modally tuned impact hammer with force sensors and an array of accelerometers, displacement and force transducers.

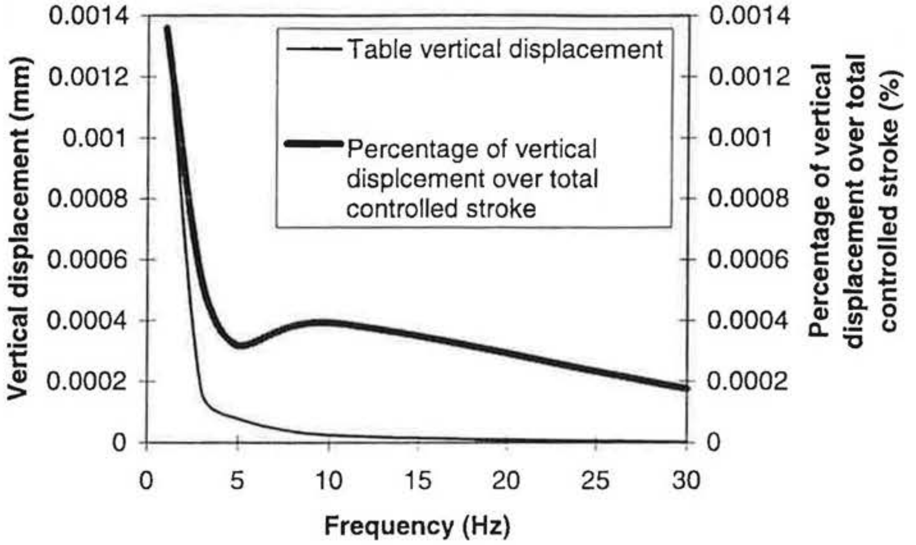

Figure 3: Vertical displacements of shaker table when excited by horizontal input signals listed in Table 2

6. COLLABORATIVE RESEARCH WITH INDUSTRY

An important goal in establishing this Facility was to provide a centre for leading edge needs driven, research and development of national significance in collaboration with industry. It is also envisaged that the testing facilities will assist Australian designers, manufacturers and contractors to develop and test products and designs to meet the requirements of countries in the pacific rim region many of which are in highly seismic zones and are subject to tropical storm hazards. Arrangements for the conduct of collaborative research and development programs will be flexible to reflect the needs of industry. such arrangements may vary to from the use of the testing facilities by external groups to contract research undertaken by UTS personnel. To facilitate implementation of effective collaborative projects, prospective users of the facility can call on the expertise of experienced researchers of both universities to assist with the planning and conduct of a proposed research development or testing program.

7. CONCLUSIONS

The National Facility for Dynamic Testing and Research provides a high performance programmable shaker table which incorporates advanced hydraulic and control technologies. The Facility provides a versatile environment for the conduct of dynamic testing and research on prototype sized specimens. The facility is equipped with state-of-the-art data acquisition instrumentation and analysis software.

NUMERICAL SIMULATION MODELS FOR EARTHQUAKES AND SEISMIC WAVES: TOWARDS AN IMPROVED ABILITY TO QUANTIFY THE EARTHQUAKE HAZARD

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David Place received an M.Sc. in parallel computing from Lile University in France in 1994 on earthquake simulation. He is nearing completion of his Ph.D. on numerical simulation of the physics of earthquakes at QUAKES.

Fabien Coutel obtained his M.Sc. degree from the Institut de Physique du Globe, Paris, France in 1993 on seismic modelling. He is currently working towards his Ph.D, on this topic at QUAKES, and its application to site amplification studies in detailed earthquake hazard assessment.

Yong Zeng obtained a Ph.D. degree in Engineering Geology from Chengdu Institute of Geology, China in 1990. He then worked as a research fellow at the State Seismological Bureau and subsequently, as a visiting research fellow at the Institute of Geological and Nuclear Sciences, Wellington, New Zealand. In 1996, he commenced Ph.D. studies at QUAKES on the topic of simulating seismicity sequences and earthquake hazard analysis.

ABSTRACT:

A paucity of data and limited understanding of spatio-temporal variability of intraplate seismicity renders probabilistic earthquake hazard analysis unreliable in Australia. Another problem in quantifying the earthquake hazard is posed by limitations in methodology to estimate seismic wave amplification. Numerical models that enable the complete earthquake cycle to be simulated would provide powerful tools to study earthquake behaviour and facilitate development of new approaches that better predict the earthquake hazard. QUAKES is focussed on developing such models to complement its observational program to monitor the earthquake hazard in Queensland.

The particle based lattice solid model simulates the underlying micro-physical processes controlling earthquake generation. Recent results demonstrate this model is able to simulate nonlinear behaviour such as the dynamics of slip and development of fault gouge, and yields realistic statistical properties for stress drops and event sizes. Studies using the approach may ultimately lead to improved earthquake assessment methodology.

Macroscopic simulation studies of seismic waves in a model of Brisbane have lead to the conclusion that some common observational approaches used for micro-zonation are unreliable. In particular, micro-tremor analysis using Nakamira's method is generally unable to predict even the fundamental frequency of amplification in the presence of non-flat geologic structure.

1 INTRODUCTION

A quantitative understanding of earthquakes and their effects is essential to mitigate appropriately against this natural hazard. In Australia, there is a paucity of historical and recorded seismic data that renders probabilistic earthquake hazard analysis unreliable as evidenced by major changes in hazard maps as additional data becomes available[1]. In addition, some of the underlying assumptions of probabilistic analyses are questionable such as spatio-temporal invariance of seismicity patterns and Gutenburg-Richter statistics in any given localized region.

An ability to simulate the physics of earthquakes and the complete earthquake cycle would provide a powerful tool to study earthquake behavior. This could ultimately enable new approaches to be devised that better predict the level the earthquake hazard from the available observations. Similarly, an ability to simulate seismic waves in complex 3D structures will lead to an improved ability to map local variations in the earthquake hazard due to seismic wave amplification effects. QUAKES is focussed on developing such numerical simulation models to complement its observational program to monitor the earthquake hazard in Queensland.

2 SIMULATION OF THE PHYSICS OF EARTHQUAKES

The lattice solid model[2,3] is a particle based approach that was motivated by molecular dynamics principles, but with particles representing aggregate units such as rock grains or blocks instead of atoms. The model has the essential characteristics to allow all the relevant physical processes associated with earthquakes to be simulated in a relatively straightforward manner including stress transfer, generation and propagation of seismic waves, fracture, evolution of complex systems of faults and fractures, evolution of fault gouge and shear zones, friction, thermal effects, and fluids etc. The snapshots depicted in Figure 1 illustrate the models ability to simulate fracture and gouge development around model faults.

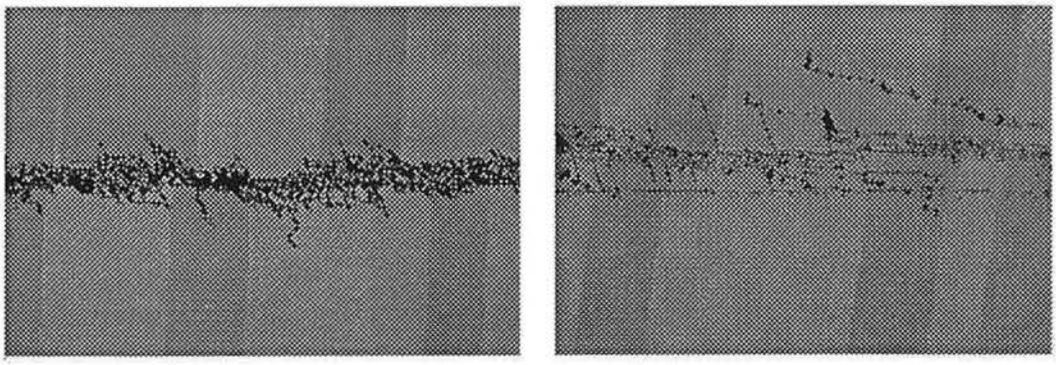


Figure 1: Snapshots showing fractures and gouge that developed around simple initial model faults.

In the current version the model consists of a 2D system of interacting particles. These are linked by elastic-brittle bonds in solid regions. Unbonded particles that come into contact, such as at the edges of two touching surfaces, interact through frictional and repulsive forces. Particle positions are extrapolated during the simulations using an explicit finite difference approach. A precise numerical solution that captures the passage from static to dynamical frictional behavior between particles is non-trivial and has necessitated development of a new computational approach[4].

Recent numerical experiments[5] using the lattice solid model that involved a model transform fault have shown that when fault gouge is present, the effective fault friction may be reduced to a level far below that of rock surfaces. The effective friction or strength of the model fault is sufficiently low to offer a quantitative explanation for the 30 year old heat flow paradox*[6–8] in geophysics, and quantitatively meet the associated observational constraints. The ability of the lattice solid model to explain these previously unmet observational constraints suggests that when fully developed and in 3D, the model can be used to probe earthquake behavior. The lattice solid model could also potentially be used to simulate coupled earth/(man-made structure) systems allowing for nonlinear earth response and brittle fracture of man-made structures.

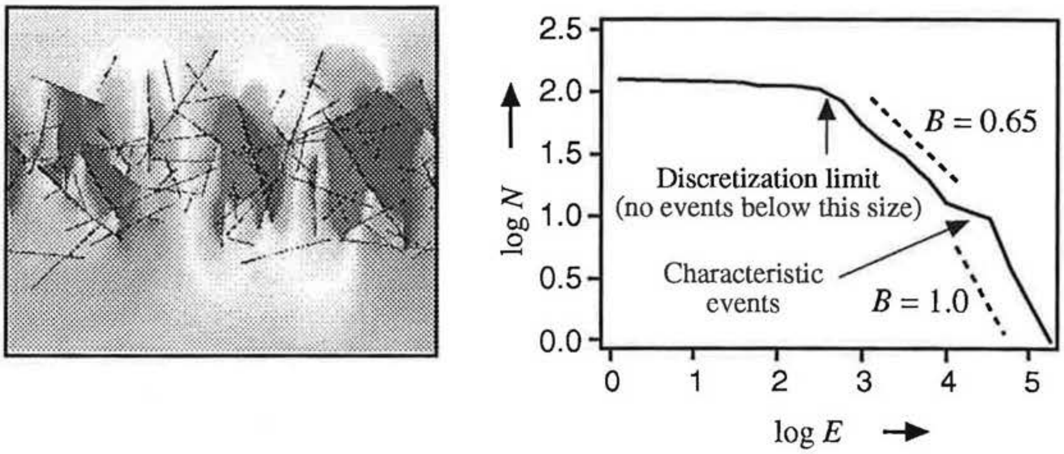


Figure 2: **Left:** A typical random fault network embedded in 2D model. The grey scale depicts the horizontal displacement in the model since the beginning of the simulation. **Right:** An example of a cumulative frequency-energy plot that shows evidence for two slopes separated by a bump at $\log E \approx 4.4$ (i.e. an anomalous number of events occur at $\log E \approx 4.4$). **Note:** $\log E = 1.5M + 11.8$ so the B-value indicated on the plot of 0.65 corresponds to a b-value of approximately 1.

A major long term goal is to enable earthquake recurrence and spatio-temporal variability of seismicity to be studied. Preliminary results have demonstrated that the model is capable of reproducing realistic and varied statistical features such as Gutenberg-Richter (G-R) frequency-magnitude distributions for simulated earthquake event sizes. Typical exponents of the G-R relation are 1.0, similar to the global average (middle part of Figure 2, Right) but in some instances may be as low as 0.1 (i.e. statistics dominated by earthquakes of a given size). Such relations occur naturally in the models as a consequence of the nonlinear interactions occurring along the model faults. G-R relations are observed both for single faults[9] and multiple

* Heat flow measurements around the San Andreas fault have failed to detect any heat anomaly around this fault. This observation contradicts theoretical calculations based on fault slip rates and laboratory derived coefficients of rock friction which predict an observable anomaly.

fault systems[10]. In some instances such as Figure 2, there is evidence suggesting a cross-over from one exponent to another above a given magnitude and/or an anomalous number of events of a given size (i.e. characteristic earthquakes). The study of the conditions that yield these different behaviors in the numerical model may ultimately provide insights that help allow non Gutenburg-Richter statistics in real data to be correctly identified and taken into consideration. This is crucial in view that the rate of occurrence of large infrequent quakes is a key factor in determining the level of the earthquake hazard. However, these rates are largely inaccessible to direct observations in Australia due to the shortness of the earthquake record. Under the current earthquake hazard methodology adopted in Australia as well as many other regions, Gutenburg-Richter statistics are assumed, and a straight line is fit to the earthquake frequency-magnitude distribution to extrapolate the frequency of large potentially damaging earthquakes. However, this assumption may be invalid and the resulting estimates of earthquake hazard levels erroneous in any given localized region.

3 SIMULATION OF SEISMIC WAVE AMPLIFICATION

An important modifying factor of the earthquake hazard is amplification of incoming seismic waves by local geologic structure. Quantification of the earthquake hazard requires mapping of these local variations in the earthquake hazard which superimpose on the regional hazard picture. A knowledge of the complete spectrum of the ground response due to seismic waves generated by a large earthquake is desirable (i.e. frequency and amplitude of amplification). However, large earthquakes are relatively infrequent at any given location so observational approaches used in Australia for micro-zonation studies are typically based on micro-tremor noise measurements.

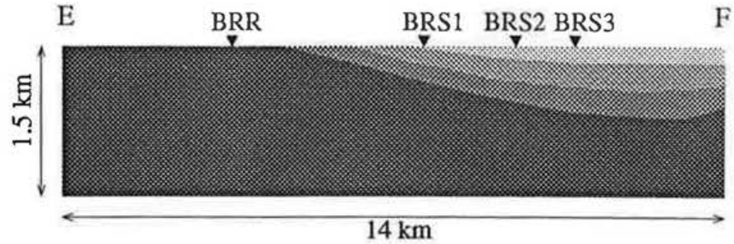
The pseudo-spectral method[12,13] enables seismic waves to be accurately simulated in the presence of complex earth models with non-flat surface topography. This approach provides a powerful tool to determine ground response due to incoming seismic waves provided accurate earth models are available. The approach also provides a means to probe the limits of applicability of existing observational approaches, and to devise and test new field methods.

Numerical experiments have been conducted to study some of the frequently used observational approaches to estimate site amplification effects[11]. Specifically, we simulate micro-tremor noise in given models and compute the Sediment to Bedrock Noise Ratio (SBNR) and Horizontal to Vertical Noise Ratio (HVNR). These results are compared to the estimated "true" response of the models due to incoming S-waves at specific incidence angles computed using the Sediment to Bedrock Spectral Ratio (SBSR). We also compute the Horizontal to Vertical Spectral Ratio (HVSR) in these cases for comparison with the true response response given by SBSR. In Australia, the Horizontal to Vertical Noise Ratio (HVNR) is frequently used in micro-zonation studies.

The above spectral ratios were computed at several sites along a 2D cross section approximating the subsurface structure between Brisbane airport and the City*. The model and spectral ratios at two sites are shown in Figure 3. The results illustrate

* The cross-section was based on seismic refraction studies and surface maps.

Layers	V_P	V_S	ρ
1	710	410	1700
2	1580	910	2000
3	3200	1850	2500
Base	5000	2890	2800



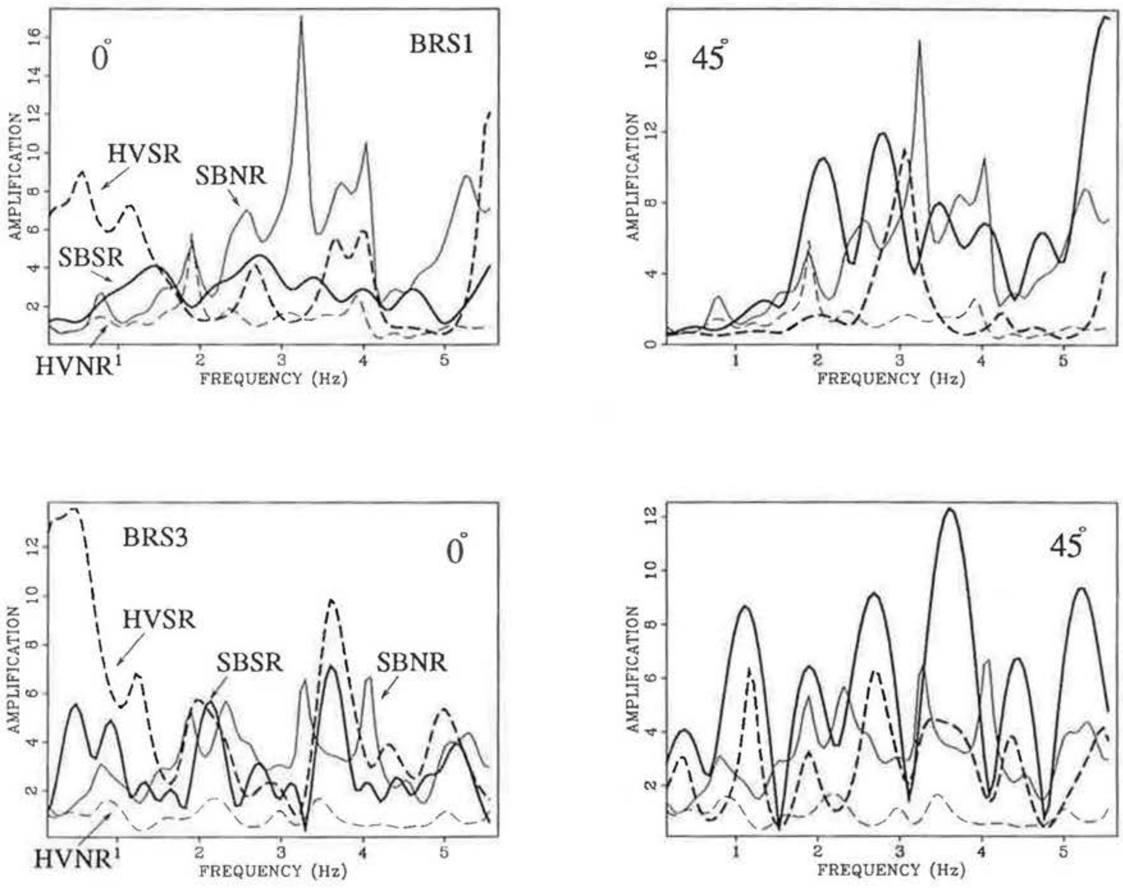


Figure 3: **Upper:** 2D earth model showing location of sites BRS1 and BRS3. **Middle:** Spectral ratios at site BRS1 located at the edge of the basin. **Lower:** Spectral ratios at site BRS3 located in the middle of the basin where the geologic layers are almost flat. **Note:** The spectral ratios based on micro-tremors (HVNR and SBNR) compare poorly with SBSR which represents the true response of the site for incoming S-waves at the specified incidence angles of 0 degrees (vertical) and 45 degrees.

that in the presence of structure (i.e. near the edge of the basin as for site BRS1), observational methods based on analysis of micro-tremor noise are generally unable to predict either the frequency or amplitude of peaks in the spectrum, including the fundamental mode. Furthermore, one observes major changes in the true response (SBSR) with incidence angle of the incoming wave. At site BRS3 where layers are almost flat, the location of peaks in the spectral ratios (but not amplitude) are more similar than at site BRS1 near the basin edge where the layers are dipping. However, similarity begins to be lost at higher incidence angles.

The results suggest that information on the spectral response of sites derived from micro-tremor surveys may be unrepresentative of the true response of the earth during an earthquake. Hence, while micro-tremor surveys provide valuable data about sites that are potentially prone to amplification, the simulation studies suggest they yield little quantitative information on the true spectral response of the earth. Micro-tremor based spectral ratios are expected to be particularly unreliable at sites where the local geology contains structure, or as predictors of earth response due to far from vertical incidence waves, the case generally expected in Australia (i.e. earthquake sources tend to be shallow in Australia so incoming waves would generally be closer to horizontal than vertical).

Ultimately, a 3D simulation capability is required for studies of site amplification effects. Hence, the pseudo-spectral approach is presently being extended to 3D.

4 CONCLUSIONS

A new microphysically based model is being developed that aims to allow the complete earthquake cycle to be simulated. When fully developed, this model will provide a powerful tool for studying the earthquake generation process and developing improved capabilities to predict the earthquake hazard using the limited available data. Simulations using the model in the current form show a richness of phenomenology that illustrates the potential of the approach. Recent numerical results have provided a comprehensive explanation for a long-standing geophysical paradox and yield realistic frequency-magnitude statistics of earthquake events.

Macroscopic simulation studies of seismic waves in a model representative of the structure under Brisbane have lead to the conclusion that some widely used observational approaches (using micro-tremor surveys) in micro-zonation studies are unreliable in the presence of structure or when the incident waves are non-vertical. The simulation results suggest that micro-tremor derived spectral ratios are generally dissimilar to the true response of the earth due to a given earthquake. The wave simulation capability provides a tool to enable the true ground response to be predicted if a detailed subsurface model is available. When such models are unavailable and survey costs to gain this information cannot be justified, less expensive observational methods will continue to be useful. In this case, the wave simulation capability will help allow new observational approaches to be devised that more reliably quantify the local variation of the earthquake hazard than existing methods.

Acknowledgments. Principle computations were made using QUAKES' 3.1 GFlops Silicon Graphics Origin 2000 parallel supercomputer. Supplementary computations were made using the Silicon Graphics Power Challenge supercomputer of The University of Queensland. Principle funding for this research was provided by the Australian Research Council. Additional support has been provided by The University of Queensland and sponsors of QUAKES (Amoco Production Company, Brisbane City Council, Cairns City Council, Charters Towers City Council, Department of Main Roads, Silicon Graphics Pty. Ltd.). QUAKES' earthquake monitoring and hazard program is supported by the Queensland State Government.

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ANALYSIS OF THE COLLAPSE BEHAVIOUR OF CONCRETE FRAMES UNDER SEVERE DYNAMIC LOADING

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ABSTRACT:

This paper presents the preliminary results from an analytic study of the non-linear dynamic behaviour and collapse of stocky and slender concrete portal frames subjected to severe ground motion. The results were obtained using a computer simulation procedure that is still under development. While experimental data are needed to test the accuracy of the computational method it is numerically stable and appears to give realistic results.

Paper No. 14

1. Introduction

Current design methods for concrete structures subjected to severe earthquake loads rely on linear elastic methods of analysis that are unrealistic and inaccurate, and bear little resemblance to actual behaviour. Large correction factors are therefore used to modify the results of the linear analysis in order to achieve usable design results. The need for more realistic methods of collapse analysis as the basis for design has been recognised, both for static loads (1) and for earthquake loads (2).

In order to carry out a realistic analysis of the collapse behaviour of a frame under dynamic loading, it is necessary to take account of the material non-linearities in local regions where alternating plastic deformations occur, as well as the non-linear geometric effects in the frame as a whole. Consideration also has to be given to damping effects in the frame. Such analysis is necessarily very complex, and has to be computer-based.

The research work described in this paper is aimed at producing a reliable analysis procedure that will predict, realistically, the collapse behaviour of concrete frames under severe dynamic loads. Considerable progress has been made, and a computer simulation procedure is now available that numerically follows the developing time history of a concrete frame when subjected to impulse ground motion. Briefly, the numerical procedures are based upon classical finite element methods using Newton Raphson iteration within each step and a global tangent stiffness matrix for the frame, and a Lagrangian coordinate system to account for large deflections. Further details are given in the paper by A. Kawano(3). Various modifications and improvements are presently being developed. To check the numerical stability and robustness of the procedure, the collapse behaviour of a large number of concrete frames has been studied.

In order to illustrate the potential of the method, some results are presented in this paper from a study of the collapse of a stocky and a slender concrete portal frame.

2. Collapse analysis of stocky and slender frames under ground motion

The computational details given in Fig 1 show the locations of the elements and the numbering of the nodes for both frames. The frames were similar, except for the height of the columns. The span was 5 m, with heights of 1.6 m and 10 m respectively for the stocky and slender frames. The beam was 200 mm wide with a total depth of 400 mm, and contained two per cent reinforcement in both the negative and positive moment regions. The columns were 200 mm square, and contained a total of four per cent steel reinforcement. The strength of the concrete was 30 MPa, and the steel was assumed to have a yield stress of 400 MPa. Masses of 0.5 tonne were assumed to be concentrated at each corner of the frame, ie at nodes 1 and 5. In addition, two constant vertical loads P (as shown in Fig. 1) acted downward at nodes 1 and 5, ie along the axis of each column. An impulse ground motion of Δ mm was applied over a period of 0.04 seconds.

Fig 2 shows the response displacement of node point 1 as a function of time for the stocky frame. Values of axial load P ranging between P = 1425 kN to P = 675 kN were considered. Typical results for P = 800 kN are shown in Fig. 2. For this case a ground movement of 100 mm produced only elastic oscillations that attenuated after about 0.5 seconds, with no significant permanent deformation. For the case of Δ = 200 mm, the initial oscillations were inelastic, but settled down to a permanent displacement of around 100 mm. A ground motion of Δ = 225 mm was sufficient to create an exponential increase in response displacement, with collapse at around 0.2 seconds. Larger ground displacements also lead to collapse, but even more rapidly. The effect of varying P was to change the critical value of Δ required to cause collapse. For example, at P = 1425 kN, collapse occurred with Δ in the range 40 - 48 mm, whereas with P = 675 kN, a Δ value of 225 - 250 mm was required.

For the slender frame, impulse ground motions of 250, 300, 350 and 400 mm were used with P values of 300, 325, 350 and 375 kN. Typical results are presented in Fig. 3 for the case where P = 300 kN. For this load, the impulse displacements of 250 and 300 mm produced elastic oscillations and no significant permanent deformations. With Δ = 350 mm, plastic deformations clearly occurred and the permanent displacement offset was somewhat more than 200 mm. Only with Δ = 400 mm did collapse occur. However, for P =375 kN, all impulse displacements resulted in collapse. Not surprisingly, these results suggest that the behaviour of the slender frame is very sensitive to the magnitude of the permanent vertical load P. Simple collapse load calculations, made as an order-of-magnitude check, showed reasonable consistency with the results of the computer simulations. The relatively large deflections in the slender frame were also expected.

3. Further work

The computer simulation program is being further developed and extended. In particular, an element is being created to model inelastic behaviour in regions of high alternating moment, in the presence of axial force and alternating shear. The current elements presently do not allow adequately for shear deformations and the criss-cross inclined cracking that occurs in such hinge regions.

In all of the simulations undertaken to date, a simple impulse ground motion in one direction has been used as input, in order to limit the computational time. A more complex, alternating ground motion corresponding to a severe earthquake can nevertheless be treated computationally. Such cases will be considered in future work.

However, experimental confirmation of the accuracy of the computational procedure is now urgently required. This presents considerable difficulty, because of the paucity of real dynamic test data. Most experimental data on the response of large-scale concrete frames to earthquake loads come from pseudo-dynamic tests, which do not take proper account of the inertial effects. At the present time, an attempt is being made to develop a test procedure using small, highly nonlinear and inelastic model frames on an existing shaking table. While the small model frames will not be accurate representations of real concrete frames, the experimental data generated will provide accurate dynamic data with which to test the accuracy of our computational procedures.

4. Concluding remarks

This paper presents preliminary results from an analytic study of the non-linear dynamic behaviour and collapse of a stocky and a slender concrete frame subjected to severe ground motion. The results were obtained using a computer simulation procedure that is still under development. While experimental data are needed to test the accuracy of the computational method, it is numerically stable and seems to give realistic results.

In summary, the prime aim of this work is to develop realistic methods of analysis of dynamic collapse, which can be used for design. However, the simulation procedure, when fully developed and tested, will also provide a means of identifying and evaluating errors in the elastic methods currently used, and hence may allow improved values to be obtained for correction factors such as R_f.

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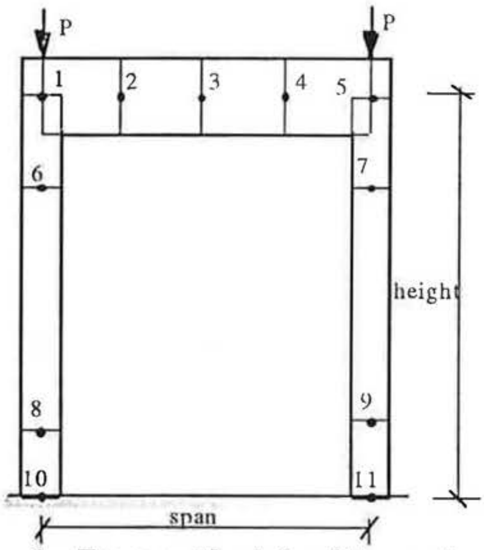
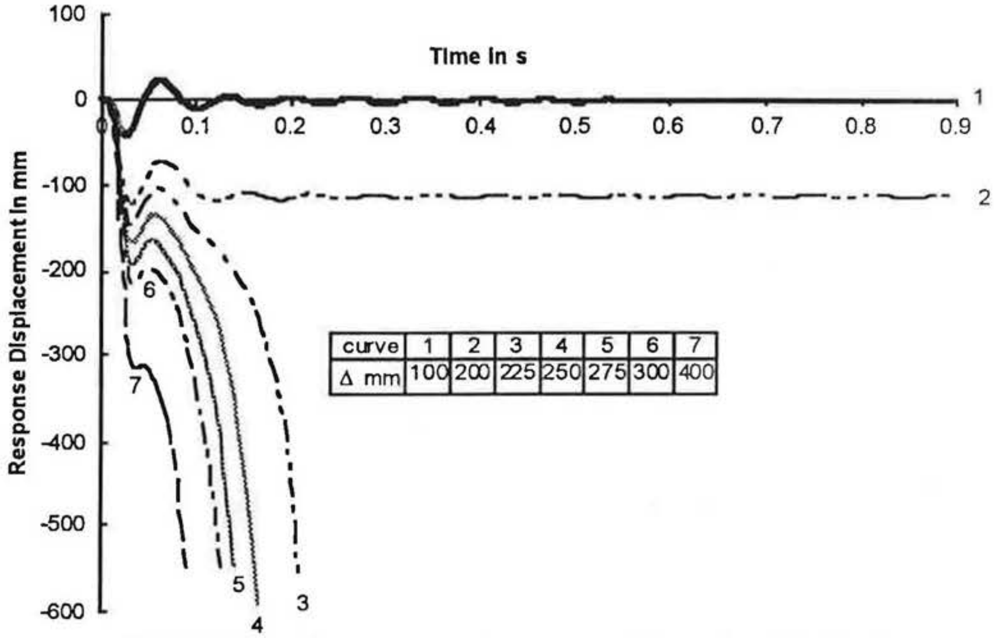
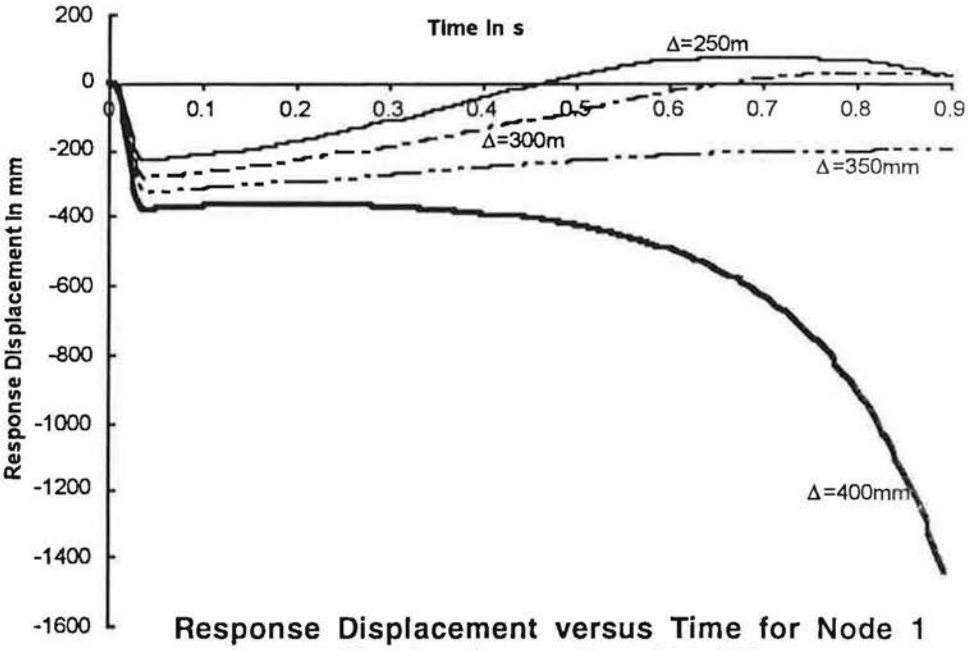


Fig. 1: Frame Model with node numbers



Response Displacement versus Time for Node 1
Stocky frame, P = 800 kN
Figure: 2



Response Displacement versus Time for Node 1
Slender frame, P = 300 kN
Figure: 3

RESEARCH INTO THE SEISMIC PERFORMANCE OF UNREINFORCED MASONRY WALLS

ALPHAN NURTUG, KEVIN DOHERTY, JOHN WILSON, NELSON LAM AND MIKE GRIFFITHS

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ABSTRACT:

Previous research has highlighted out of plane bending and connections as the weak links in the seismic load path for unreinforced masonry (URM) walls. As a consequence a three year collaborative research program betweeen the University of Melbourne and the University of Adelaide has commenced early this year to investigate the earthquake response of URM walls. This paper provides an outline of the experimental and theoretical studies carried out to date on the bending strength of simply supported and parapet walls together with the dynamic frictional coefficients of damp proof courses (DPC) and slip joint membrane type connectors. The proposed study direction for the remaining years is also briefly discussed.

Paper No. 15

RESEARCH INTO THE SEISMIC PERFORMANCE OF UNREINFORCED MASONRY WALLS

NURTUG, A.[1], DOHERTY, K.[2], ,GRIFFITH, M.[2], LAM, N.[1], WILSON, J.[1]

ABSTRACT

Previous research has highlighted out of plane bending and connections as the weak links in the seismic load path for unreinforced masonry (URM) walls. As a consequence, a three year collaborative research program between the University of Adelaide and the University of Melbourne has commenced early this year to investigate the earthquake response of URM walls. This paper provides an outline of the theoretical and experimental studies carried out to date on the bending strength of simply supported and parapet walls and the dynamic frictional shear strength of damp proof course (DPC) and slip joint membrane type connectors. The proposed research direction for the remaining years is also briefly discussed.

INTRODUCTION

The 1989 Newcastle earthquake in New South Wales, Australia reminded us that brick buildings are most vulnerable to earthquake damage. A similar event in a capital city such as Sydney or Melbourne is expected to result in even greater casualties and damage. A three year collaborative research program between the Universities of Adelaide and Melbourne has commenced early this year to investigate the seismic integrity of unreinforced masonry (URM) walls with the aim of formulating design recommendations to mitigate the seismic risks.

The research will focus on the weak links in the seismic load path system for URM buildings identified by Klopp and Griffith, 1994 (1) as being the limited force capacity of the support connections and inadequate out-of-plane bending strength of walls. The results of tests completed to date and future research work are discussed in this paper.

DYNAMIC SHEAR CAPACITY OF CONNECTIONS CONTAINING DPC MEMBRANES

DPC membranes are impervious materials often incorporated into a mortar joint as a means of preventing moisture movement in masonry walls. Being a plane of separation this prevents cracking due to differential movement between a wall and its supports. However, the connection must also be capable of transmitting horizontal seismic forces. AS1170.4 Part 4 'Earthquake Loads' (2) requires that connections be designed for a minimum horizontal force of 10 (aS) kN/m where a is the acceleration coefficient and S is the site factor. In AS3700, SAA Masonry Code (3), an equation is given for estimating the horizontal shear capacity of a DPC connection, which contains a Coulomb friction component and a bond component. Unless substantiated by appropriate tests the friction component is taken as zero, which requires the design shear force to be resisted by solely the bond component.

In Australian masonry construction it is common practice for DPC membranes to be placed directly onto bricks as opposed to be sandwiched within a mortar joint. With no bond strength component, this connection is dependent on friction to resist horizontal shear force. This has serious design ramifications, as without friction there is no load path for horizontal forces. It is therefore

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important that a sound understanding of the frictional properties of DPC connectors be developed so that reliable design values for friction can be established. Page, 1994 (4) has already investigated static friction coefficients for a number of DPC connections commonly used in Australian masonry construction. As a result he has recommended that, conservatively static friction coefficients for design may be taken as 0.3.

To investigate the dynamic frictional properties of these connections a preliminary series of dynamic shaking table tests have been performed at the University of Adelaide. Both DPC and slip joint (no mortar) connections have been tested. A harmonic, sinusoidal signal was used to drive the earthquake simulator in displacement control and the amplitude gradually increased until definite slip occurred. For each test the slip was noted to be at the interface of DPC and brick. The upperbound dynamic shear force was then used to calculate the dynamic coefficient of friction for each of the connections. The dynamic values are then compared with the static coefficients determined by Page (4) and are shown in Table (1).

The dynamic μ appeared to be up to 35% less than the static value. This has some ramifications for the seismic design of these connections.

Table (1) - Preliminary test results

Test Description	Dynamic μ	Static μ	Dynamic μ / Static μ
DAMP PROOF COURSE (DPC) - IN PLANE TESTS			
Embossed Polyethylene	0.39	0.59	**66%**
Alcore-bitumen coated aluminium	0.38	0.49	**77%**
SLIP JOINT (SJ) - OUT-OF-PLANE TESTS			
Standard Alcore	0.36	0.57	**64%**
Two Layers of Standard Alcore	0.44	0.48	**91%**
Abafel with Molybdrum Sulphite Grease	0.09	0.07	**133%**

OUT-OF-PLANE BENDING CAPACITY OF SIMPLY SUPPORTED URM WALLS

In AS3700 (3) the design methodology for vertical bending of URM walls from transient out-of-plane forces employs a linear elastic analysis of the uncracked section. This considers the stresses on the leeward face as a combination of both compressive stress, from precompressive load and self-weight, and characteristic flexural tensile strength, f'_{mt}. In the absence of test data AS3700 (3) requires f'_{mt} to be taken as 0.2 MPa with a capacity reduction factor, C_m of 0.6. Secondary effects such as arching, fixity of supports and superimposed load all have a beneficial effect on the flexural strength of a wall. Unfortunately they also make direct comparison with other experimental results difficult. As the linear elastic analysis is more appropriate to a monotonically increasing static load preliminary shaking table tests have been undertaken at the University of Adelaide to investigate the adequacy of this design methodology for dynamically loaded walls. Two tests have been completed to date.

In each of the tests two walls were tested in parallel and orientated at right angles to the direction of shaking. Each wall sat on a DPC connection and was supported laterally at the top by a 'cornice' type restraint. Although these support conditions were by no means simple supports, the rocking induced at the base of the wall about the leeward face, was taken into account. A harmonic, sinusoidal signal was used to drive the earthquake simulator at a frequency of 2 Hz. The displacement amplitude was gradually increased until flexural failure occurred.

Using the design methodology of AS3700 (3), with f'_{mt} equal to 0.2MPa the vertical bending capacity of the walls was calculated to be reached at an input acceleration of 0.44g. A linear elastic analysis for an uncracked section with a mean flexural tensile strength and no capacity reduction factor indicates that an acceleration of 1.5g would be required to cause failure. A similar analysis for a fully cracked section at mid height provides a lowerbound estimate of 0.28g to cause wall failure.

Both test walls were found to fail at an acceleration of approximately 0.45g, being much lower than that predicted by linear elastic analysis. The reasons for this significant difference are still being investigated.

ROCKING CAPACITY OF URM WALLS

Various aspects associated with the rocking capacity of URM walls such as, the non-monotonic nature of rocking, phase angle, frequency contents and durations for different sets of artificial and real earthquake ground motions have been investigated in a previous study at the University of Melbourne. In the experimental stage, a 0.9m high single-skin URM cantilever wall was tested on a shaking table (5,6). The masonry units were traditional extruded clay building bricks of dimensions 230mm x 110mm x 76mm with a mean characteristic compressive strength of 50MPa. The masonry mortar, prepared with 1 part Type A Portland Cement, 1 part hydrated lime and 6 parts sand, had an average flexural tensile strength of 0.2MPa determined from bond wrench tests. A large number of dynamic tests were carried out to determine the response characteristics of the wall in both the uncracked and the cracked state. A non-linear time-history analysis program was then developed to model the rocking behaviour. The program assumes a rigid behaviour up to the threshold of rocking and then a negative stiffness, to take into account the P-delta effect, during rocking. The theoretical response of the wall to simple pulses predicted by the program were found to match reasonably well with that obtained from the experiments.

The natural rocking frequency of the wall was not constant but dependent on the tip displacement of the wall. This effect can be identified by the frequency versus amplitude relationship, measured during a series of tests, in which the wall was initially displaced and allowed to rock freely. Figure 3 shows the rocking frequency versus displacement amplitude relationship. The measured rocking frequency was initially at 4 hertz when the displacement was very small, but rapidly dropped to below 1 hertz when the displacement exceeded 20mm.

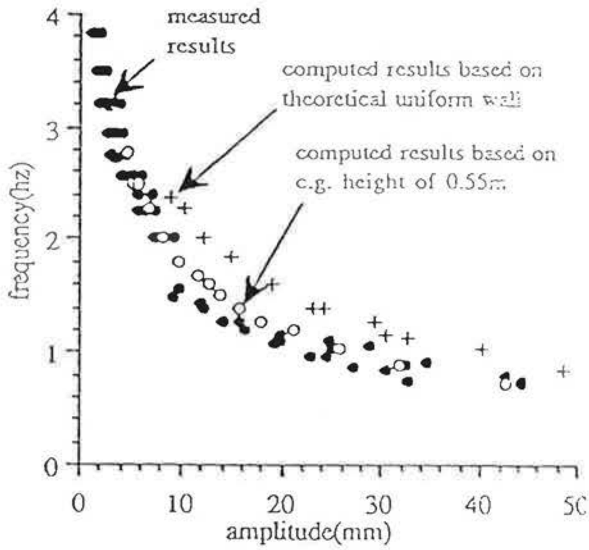

Figure 3. Experimental and theoretical natural rocking frequencies

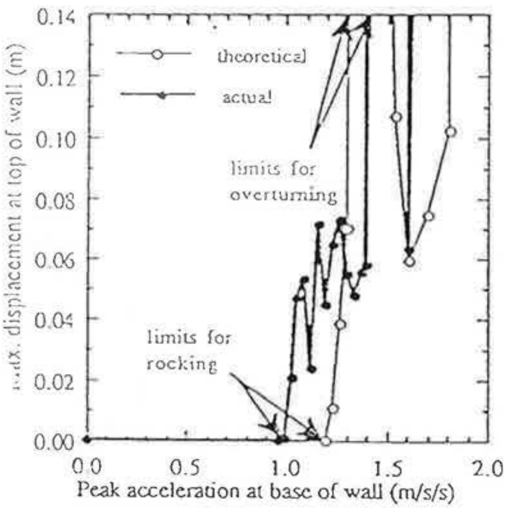

Figure 4. Peak wall displacement with increasing excitation intensity

The rocking response of a freestanding wall as obtained from the shaking table tests and the time-history analyses was highly non-linear. The maximum wall displacement did not generally increase monotonically with the increasing intensity of the excitation as shown in Fig. 4. In some instances, the maximum displacement in the wall was found to increase, as the excitation intensity was decreased, and vice versa. To determine accurately the rocking capacity of the wall, the earthquake excitation was repetitively applied to the wall, with a slightly increased intensity each time, until failure.

Artificial time-histories with a similar response spectrum, frequency content and duration but generated using random phase angles (which dictate the sequence of pulse arrivals) were used to excite the wall and compare the response. The 18 synthetic accelerograms, each with a 12 second duration, had a frequency content compatible with the design response spectrum stipulated by the Australian Earthquake Loading Standard AS1170.4(1993) (site factor=1.0). The peak excitation accelerations required to overturn the wall as derived from all 18 accelerograms, varied between $1.1 m/s^2$ and $1.5 m/s^2$, with an average of $1.3 m/s^2$ and a standard deviation of $0.1 m/s^2$. The responses of the wall to different accelerograms were clearly very different demonstrating the significance of the phase angle effects.

A further 18 synthetic accelerograms, each of 12 seconds duration, were generated from the intraplate spectrum proposed by Scott et. al.(7) for bedrock, which is characterised by a response spectrum, possessing a higher frequency content. The average overturning acceleration of the wall derived from these accelerograms was $2.4 m/s^2$, which was 85% higher than the average value calculated previously based on the frequency content of the AS1170.4 design response spectrum. An additional set, consisting of 18 synthetic intraplate accelerograms was generated with a shorter duration of 7 seconds. The average acceleration to cause overturning increased to $3.0 m/s^2$, suggesting that the stability of a to overturn a cantilever wall significantly depends on the duration as well as the frequency content of the earthquake excitation.

CONCLUSIONS AND FUTURE RESEARCH

From the limited number of connector tests performed to date the dynamic friction coefficient was found to be up to 35% less than the static values reported by Page. Further testing is proposed to substantiate these results and an apparatus capable of more efficiently testing the dynamic frictional capacity of DPC connectors is now being developed.

As currently only two out-of-plane wall bending tests have been carried out, further tests, in addition to the two out-of-plane tests already undertaken, will be completed to investigate the dynamic behaviour of URM walls. Variables such as rate and duration of loading, slenderness ratio, thickness and precompression will be investigated. It is expected that as an outcome of this research Australian designers will be provided with feedback on the suitability of standard connectors in URM construction for seismic design and confirmation of a suitable design methodology for brick walls under the action of out-of-plane seismic loads.

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INVESTIGATIVE SEISMIC TESTS OF CONTROL EQUIPMENT FOR A NUCLEAR POWER STATION

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Professor Steve Bakoss, Professor of Civil Engineering, has over twenty five years of experience in structural engineering, his main research interests relate to computational mechanics of the non linear behaviour of structures, the assessment and remediation of structural damage and new technologies for extending the service life of structures. He has extensive structural design experience; and has served Australian Standards Committees and as Head of the School of Civil Engineering at UTS..

ABSTRACT:

The University of Technology, Sydney was commissioned to conduct a series of investigative seismic tests on control equipment for a nuclear power station in accordance with IEC 980-1989 Standards. The main objective of the tests was to assess the performance of the control equipment under moderate to severe earthquakes. The units tested were prototypes of those to be installed at a Nuclear Power Station located in a seismic zone.

The tests provided the client with the opportunity to observe the performance of control equipment subjected to required sine beats with frequencies ranging between 6 to 10 Hz. The tests generally proved the adequacy of test units to withstand severe seismic forces.

The analyses identified a wide range of system frequencies between 4.2 and 44.2 Hz. The measured damping ratios were found to be sensitive to frequency. The measurements also confirmed the adequacy of M24 commercial grade holding down bolts.

Paper No. 16

1. INTRODUCTION:

The University of Technology, Sydney, was commissioned to conduct a series of investigative seismic tests on control equipment for a nuclear power station in accordance with *IEC 980-1989 Standards : Recommended Practice for Seismic Qualification of Electrical Equipment of the Safety System for Nuclear Generation Stations*. The main objective of the tests was to assess the performance of the control equipment under moderate to severe earthquakes. The units tested were prototypes of those to be installed at a Nuclear Power Station located in a seismic zone. This paper summarises the testing procedure adopted and outlines the results of subsequent analyses and the conclusions reached.

2. EXCITATION INPUT:

In accordance with IEC 980 International Standard provisions one of two excitation input types could be used. Either excitation type could be generated from the floor response spectra provided by the client. The provided spectra will be referred to as Required Response Spectra (RRS). For either excitation type, the amplitude of excitation input had to be adjusted until the resulting Test Response Spectra (TRS) enveloped the RRS or a significant portion thereof at the required damping level. The two excitation types are Single Frequency Sine Beats and a Random Acceleration Signal. For these tests. Single Frequency Testing was adopted as the primary excitation input. A random acceleration signal was also used for illustrative purposes without attempting to generate a proper Test Response Spectrum for it.

A train of five sine beats with five load cycles were used as input for every critical frequency. For these tests, in the absence of acceleration response data, frequencies of 6,7,8,9. and 10 Hertz were considered critical to achieve maximum acceleration response in the Required Response Spectrum.

The sine beats were separated by pauses in order to ensure no significant superposition of equipment response. To generate the beats, a modulated sine function followed by a pause was numerically generated . The frequency of the modulating function is an order of magnitude smaller than the main frequency in all cases. The amplitude of sine beats were chosen to ensure an envelope Test Response Spectrum with peak response values higher than those specified by the Required Response Spectrum. Figures 1 shows one of the generated sine beats which were used as excitation input. For each beat the corresponding Acceleration Response Spectrum was calculated. The calculated spectra forming the Test Response Spectra and the Required Response Spectrum corresponding to horizontal floor response spectrum (at 5% damping) for the specified Building of the Nuclear Power Plant are plotted in Figure 2. As can be seen from this figure the Test Response Spectra envelope the Required Response spectrum as required by IEC 980 International Standard provisions. For the sine beat tests, the peak acceleration values were equal or greater than the Zero Period Acceleration (ZPA) of the RRS which was 0.255 g in this case as seen in Figure 2. The table was able to reproduce the desired input excitation records very closely, and hence confirming the fidelity of the system.

3. UNIAXIAL AND BIAXIAL EXCITATION TESTS:

Most shaker table facilities around the world are uni-axial. They are capable of simulating specified motions along a single horizontal direction. Very few facilities are capable of producing two or three directional motions simultaneously. It is also recognised that severe ground motions usually possess a vertical component in addition to their dominant horizontal components. Consequently, IEC 980 International Standard requires seismic testing in both horizontal and vertical directions.

In order to satisfy this requirement utilising uni-axial testing facilities such as the one at UTS, the IEC 980 provisions require that the test unit (switchgear panels in this case) is attached to an inclined plane which is rigidly connected to the uni-axial table. Such an arrangement will impart both horizontal and vertical motions to the test unit. The angle of the incline plane was chosen so that the vertical component of motion is 2/3 of the horizontal component, as required by the client. Since in such cases the motion along the two directions are not independent, four tests are specified by IEC 980 in order to test in and out of phase.

4. INSTRUMENTATION:

In order to capture relevant data to determine dynamic characteristics of the test units, measure the magnitude of dynamic forces imparted on the units and analyse the performance of the panels under seismic environments, 10 high resolution accelerometers and eight strain gauges were installed at strategic positions on the units. Six accelerometers are installed on the units' frame and the base frame to measure horizontal and vertical accelerations at the top, mid height and base of the units.

The acceleration readings followed by frequency domain analysis using Fast Fourier Transformation (FFT) technique revealed vital information about dynamic characteristics and behaviour of the units as a whole and its components. These included natural frequencies and damping ratios. These results coupled with strain readings provided the necessary information by which the nature and magnitude of dynamic loads and their consequence on various components could be established.

5. RESULTS OF DYNAMIC ANALYSIS:

5.1 **Maximum acceleration responses** : The said ten accelerometers were used to record time history acceleration responses at the critical locations on the frame as well as on some components of the switchgear panel. This was done for all frequencies tested (6 Hz - 10 Hz at 1 Hz intervals). The maximum accelerations were then recorded. As expected the magnitude of these maxima were larger than the maximum acceleration response of 1.348g as predicted by the Required Response Spectrum.

5.2 **Detected frequencies :** Following a Fast Fourier Transformation of recorded output acceleration signals, several system frequencies were detected. Some were considered dominant while others were not. The lowest frequency detected was 4.2 Hz while the highest frequency below 50 Hz was found to be 44.2 Hz.

5.3 **Measured Damping Ratios :** From the measured data, six different frequencies in the range of 5 to 20 Hz were considered to be dominant frequencies. The recorded outputs were band filtered around these frequencies to convert them into single frequency records. The portion of the records corresponding to free vibration response (ie response after completion of the last sine beat) was then analysed to obtain the prevailing damping ratios at those frequencies. Log-decrement Technique was used to achieve this. The summary of results is shown in Figure 3. From this figure the following conclusions can be drawn :

(i) Damping Ratio decreases with increasing frequency.

(ii) For frequencies up to about 12 Hz the assumed damping value of 5% of critical for all components is conservative as the actual damping values are in excess of 5%.

(iii) For frequencies greater than 15 Hz the displayed damping is less than 5% and hence any analysis involving components with frequencies larger than 15 Hz must utilise the actual measured damping rather than the suggested value of 5%.

In this figure, squares, diamonds and circles show the measured damping values following the technique described while the lines are those obtained from linear regression analysis.

5.4 **Measured Strains/Forces in Holding Down Bolts :** The measured strains and the resulting forces in the holding down bolts were used to determine the induced base overturning moment as a consequence of imparting horizontal seismic forces to the panels. The same forces in the holding down bolts were used to verify the adequacy of connection details between the base of switchgear panels and the supporting base frame.

6. CONCLUSIONS:

A series of investigative seismic tests on Switchboard Panels in accordance with IEC 980 -1989 Standards were successfully completed. They demonstrated the capability of the Shaker Table Facility and the competence and experience of the staff members involved to conduct such seismic tests successfully. The tests provided the client with the opportunity to observe the performance of panels subjected to required sine beats with frequencies ranging between 6 to 10 Hz. The tests generally proved the adequacy of test units to withstand severe seismic forces. A few minor design problems were however detected and noted by the client to be addressed later.

The analyses identified a wide range of system frequencies between 4.2 to 44.2 Hz. The measured damping ratios were found to be sensitive to frequency. Components possessing natural frequencies of less than 12 are likely to have a damping ratio in excess of the assumed value of 5% while those possessing frequencies in excess of 15 Hz are likely to display damping ratios less than 5%. The measurements also confirmed the adequacy of M24 commercial grade holding down bolts.

7. REFERENCE:

IEC 980-1989 Standards : Recommended Practice for Seismic Qualification of Electrical Equipment of the Safety System for Nuclear Generation Stations.

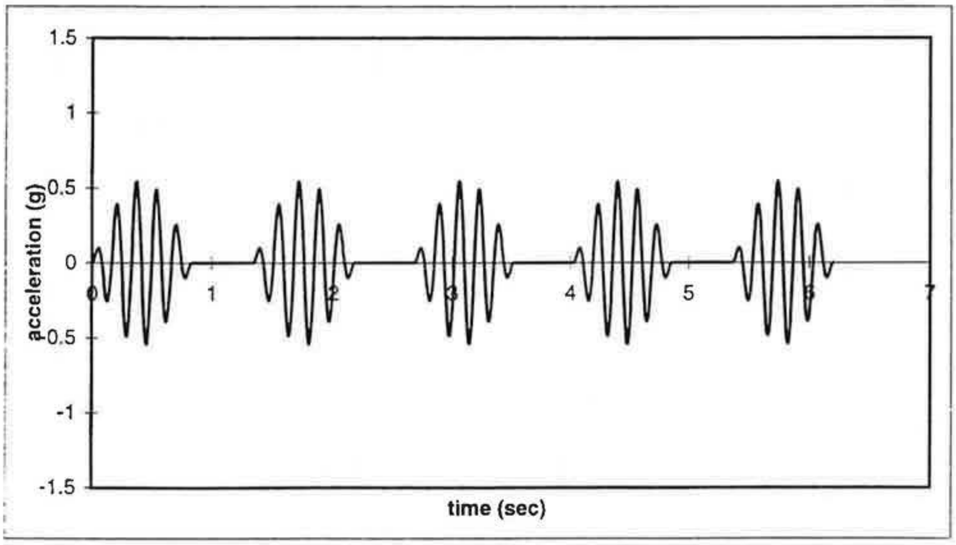

Fig. 1: Generated Sine Beats Used as Excitation Input (frequency = 6 Hz)

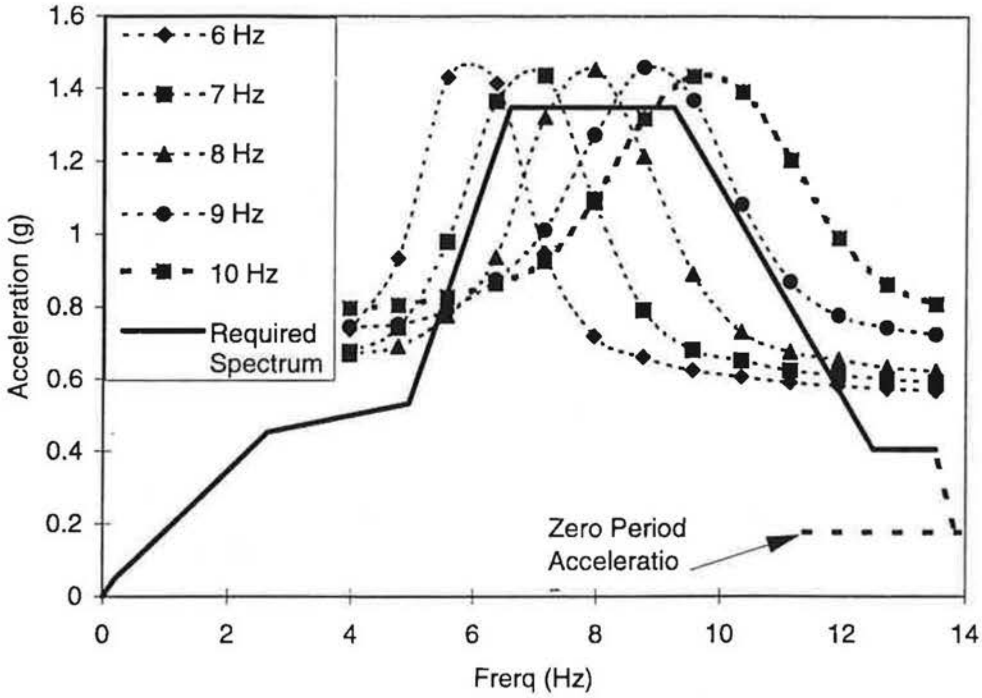

Fig 2: Required Response Spectrum for 5% damping and Test Spectra for Specified Building of Nuclear Power Plan.

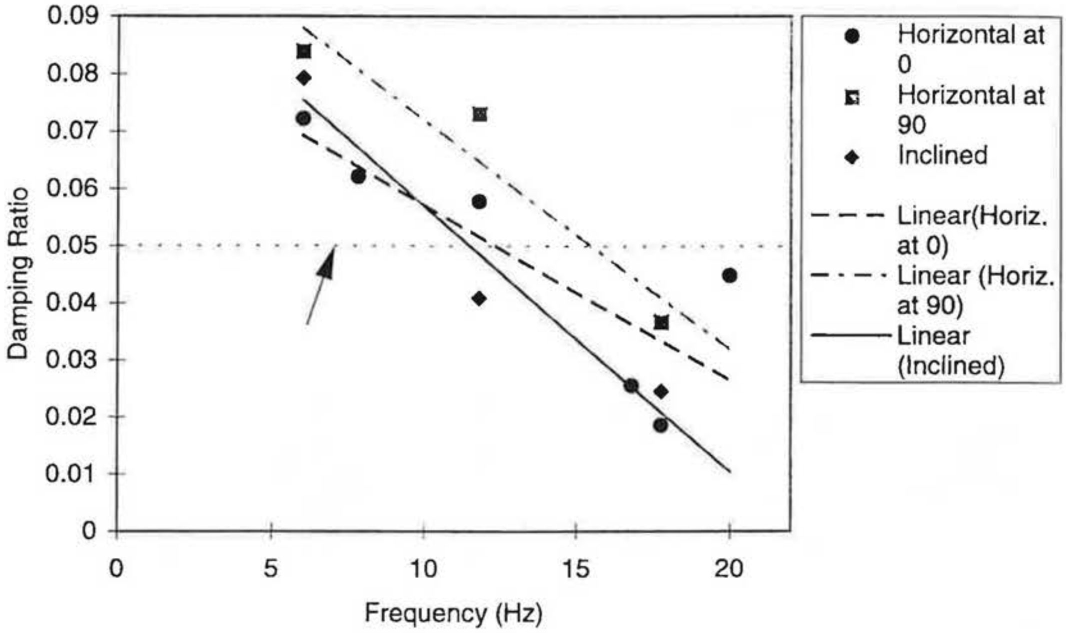

Fig 3: Variation of Measureed Damping Ratios vs Frequency

CURRENT AND FUTURE USE OF COMMUNICATION NETWORKS IN EARTHQUAKE MONITORING

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AUTHOR:

Both Vaughan and Gary have extensive experience in field seismology, operating seismograph networks and developing seismic instrumentation and software. The have also performed a wide range of seismological consulting projects, particularly in earthquake hazard analysis.

ABSTRACT:

As seismograph networks become more automated, communication between the various components becomes more important. To ensure timely response to earthquakes, this communication must be real time, or near real time. Typically a combination of systems such as radio, satellite and land lines is used. In many cases, the Internet can be used to great advantage.

This paper discusses the components of an earthquake monitoring network and the types of communication required between these components. It shows that modern seismic instrumentation and computer systems provide some of the required software and hardware but there are still many developments possible in this area.

Paper No. 17

CURRENT AND FUTURE USE OF COMMUNICATION NETWORKS IN EARTHQUAKE MONITORING

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1. INTRODUCTION

An important question facing the earthquake engineering community is why do we have seismological networks and what information do we hope to obtain from them. In the past, the answer to this question was simple: to learn about the distribution, mechanism and frequency of occurrence of earthquakes. This is still a valid answer today, but there are not many bodies willing to fund seismograph networks for this reason alone.

Much of the interest in seismograph networks today is for emergency and infrastructure management. This requires reliable and rapid response to any significant earthquake.

2. RELIABLE RAPID RESPONSE

Providing reliable, rapid response after an earthquake requires attention to many factors. The first is the need for a reliable seismograph network. The most cost effective way to provide this is with individual nodes (seismographs) which are as reliable and autonomous as they can reasonably be. More nodes should be installed than the minimum number required, providing a degree of redundancy, significantly reducing the reliability required of each node.

The second factor required is a reliable and rapid telemetry system to transport the data from the seismographs to a central analysis point. For reliability, a variety of telemetry systems should be used so that the response system does not solely rely on any one form of telemetry.

The third factor is a system that can analyse the data and perform event notification. This is usually a standard computer system of some sort, and requires standard precautions such as an uninterruptible power supply.

The final factor for this system is the event notification. The companion paper by Wayne Peck on an "Earthquake Preparation, Alarm and Response System" describes what can be done when an event is notified. The event notification can take a number of forms; systems such as pagers, mobile phones and facsimiles have been used successfully. Again, using a variety of systems is recommended.

3. DATA MANAGEMENT

Providing effective emergency response requires location of earthquakes to an accuracy of a few kilometres. This requires a fairly dense seismograph network and fairly high sample rates (50 or 100 sps). Since one cannot know in advance when an earthquake will occur, seismographs must be sampling continuously. This means that a single seismograph is collecting 50 to 100 MB of data each day. In most cases, it will not be economical to send all this data to a central recording site, therefore the seismograph must have some intelligence so that only selected data is sent. This may be anything from arrival times of suspected earthquakes to the (possibly compressed) continuous waveform of one or more channels of data. A standard telephone line will support the transfer of approximately 20 MB per day.

An earthquake analysis laboratory will typically be receiving data from between six and sixty remote seismographs. It monitors the signal coming from each recorder and determines when an earthquake has occurred. Some systems then determine an approximate earthquake location and magnitude. This information is usually then sent to a seismologist for evaluation before being released to the world at large. Another task often performed at this stage is notification of other seismic observatories, adding the information to a Web site and so on.

To aid reliability, it is suggested that in some cases data from a seismograph should be sent to more than one analysis centre. This covers the case where there is a failure in an analysis centre. It does of course bring up the question of ownership of data.

4. COMMUNICATIONS

Communications are an extremely important part of the operation of a seismograph network. Each seismograph must communicate with the analysis centre, the centre must communicate with seismologists and seismologists must communicate with each other. This paper is primarily addressing the communication between seismographs and the analysis centre.

The problematic (expensive) communication link is when a **permanent** link is required between a seismograph and an analysis centre. This is required when continuous data is required from a seismograph for real time location of earthquakes. The options at present are land lines, (digital) radio and satellite. Each option has advantages and disadvantages that must be weighed up for each site. Land lines are a simple option providing medium speed full duplex communication. However, for many seismograph sites, the cost of such a service is prohibitive (thousands to tens of thousands of dollars per year).

In recent years, great strides have been made in digital radio technology. Modern spread spectrum radios require relatively little power, no licensing, provide full duplex communications at medium speeds and can be used over distances of up to about one hundred kilometres. Relays for them are also easier than for older types of radios. However, additional power is required for the radio, and a radio mast, lightning protection and so on must be provided.

Satellite communication can provide quite high data rates where this is required. It can also be used in very remote locations. However, there is considerable additional equipment required for a satellite installation and for most users the costs are high. Costs are normally in proportion to the data flow, so there is a temptation to minimise sample rates, dynamic range and number of channels.

5. PROCESSING LEVELS

If there were no constraints on transferring data from seismographs to analysis centres, **all** the information from **all** seismographs would be sent to **all** analysis centres. The reality is that this would be too expensive. To manage this, a number of levels of processing have been introduced. Each level performs some processing on the data it receives and only passes on a proportion of the data to the next level. The idea is that the density of information in the data increases from level to level. Figure 1 shows the different components and how they inter-connect.

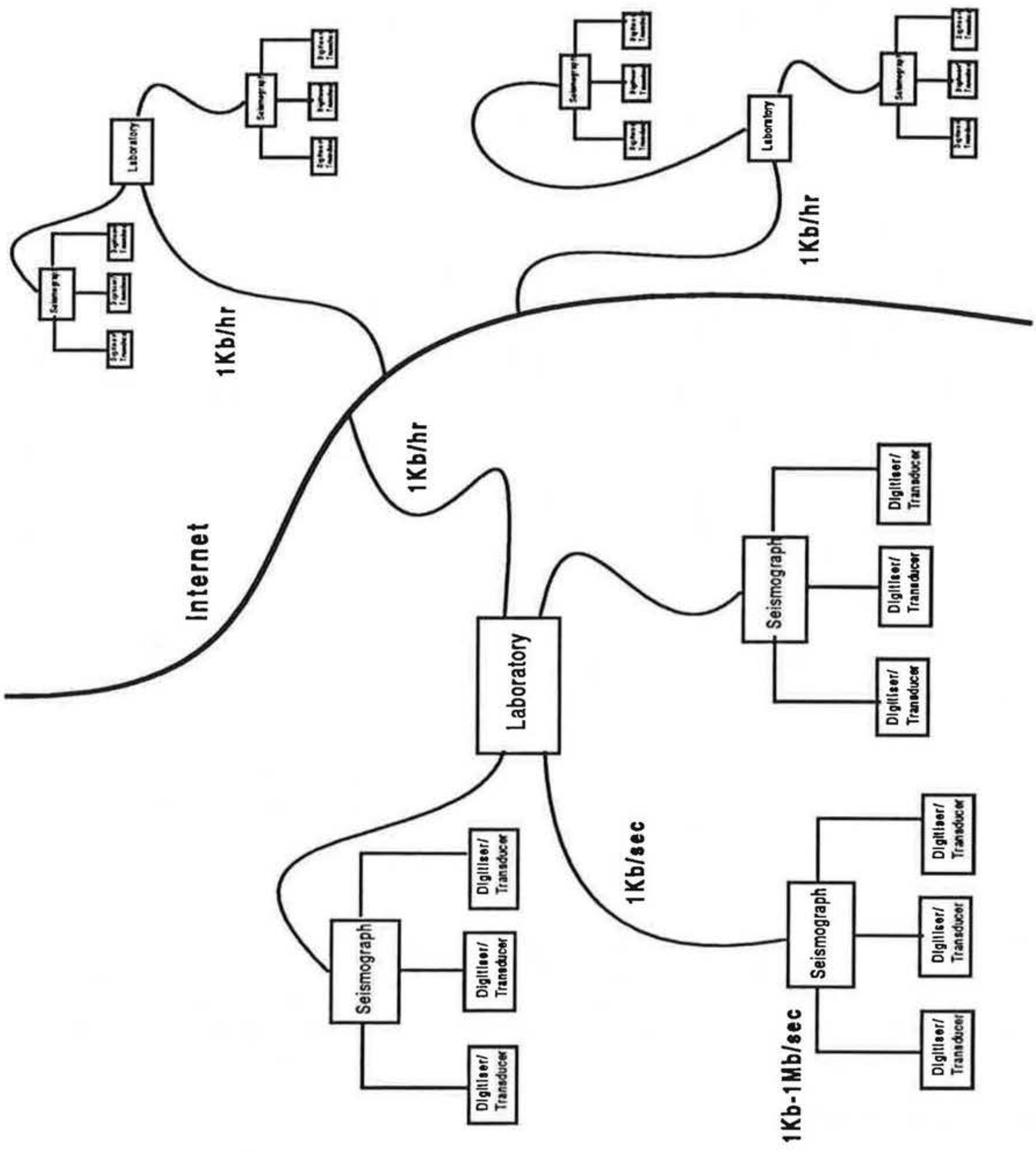

Figure 1: A network of seismograph networks

5.1 Seismograph Level

The bottom level consists of the transducer and digitising system. This system samples the signal at regular intervals and converts it to a digital value. The digitising system may be within a seismograph or external to it. More and more often these days, the data from more than one transducer is fed in to the one seismograph. This may be because both a sensitive seismograph and a strong motion accelerograph are being used, or it may be because motion is being recorded at a number of different points on a structure. In either case, the seismograph can record data from all the transducers, possibly at different sample rates.

Information from this level can be transmitted continuously, or a simple dial-up connection can be used. The optimum solution for most networks is a mixture of the two.

This level allows precise synchronisation of multiple channels, important when studying the response of a structure to earthquake motions or for small seismic arrays. It can also provide short term (hours) recording of continuous data to handle failures in the telemetry system.

5.2 Network Level

The middle level involves information from a number of seismographs being sent to an analysis centre. In many cases this is a one way communication link, to minimise costs. However, if two way communication is provided, it is also possible for the analysis centre to provide information to the recorder. This could be used for example to notify the recorder that an event has occurred which it did not detect, it would then record its data for that event in permanent storage. In many cases this data includes more channels, is at a higher sample rate and greater dynamic range than that telemetered to the analysis centre.

The communication at this level consists of moderate data rates, of the order of one kilobit per second. This can be achieved using radio, landlines or satellite telemetry. The optimum solution varies from site to site and country to country. A mix is often best.

This communication network topology is usually a star shape, all sites communicating with a central hub rather than a more general inter-connection. In some situations, data from two or more sites may be concentrated in to a single link, but the overall structure remains the same. Assuming the hub is operating, it is possible for all sites to communicate with each other through the hub although this is not often done in practice.

The analysis computers' task is to determine when an earthquake has occurred and perform the appropriate notifications. This usually means paging the on call seismologist who will then verify the information from the computer. He or she would then notify the appropriate emergency management authorities if relevant. Another important task of the system is to notify staff of any failures in the system.

An advantage provided by this level is much improved earthquake detection reliability when using a network of seismographs rather than a single seismograph. Local noise at any one seismograph will not give a false indication from the system as a whole. The other service is the ability to provide rapid information for emergency response after a significant earthquake.

5.3 Internetwork Level

It is proposed that another level is often appropriate above the individual analysis centres. It is quite possible that for one of any number of reasons, an analysis centre may be out of operation for a period of time. Since this is the hub of activities, it means that the functions performed by that network are not available. It is important however, that if the seismographs are autonomous, they will continue to operate unaffected.

To overcome this, it is suggested that analysis centres should communicate with neighbouring centres. This has not been implemented to any extent yet but is an area of active development. The availability of the Internet as an appropriate communication medium for this level has spurred activity. It opens up a number of possibilities:

- Neighbouring networks would be able to determine that an analysis centre was not operating and notify people as required. The neighbouring networks could then perform some or all of the tasks of the failed network.
- Trigger time and/or event data could be exchanged between networks providing more reliable triggering for all networks.

RECENT APPLICATIONS OF THE SEISMONITOR EARTHQUAKE PREPARATION, ALARM AND RESPONSE SYSTEM

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Wayne Peck has seven years experience in field seismology, operating seismograph networks and installation of aftershock networks. He has also been involved in a range of seismological consulting projects, particularly in earthquake hazard analysis.

ABSTRACT:

The Seismology Research Centre has been operating the SeisMonitor near real time earthquake alarm system for several years. This has recently been upgraded to incorporate time-stamped data obtained from seismographs using telemetry systems that insert unpredictable delays in transmission. This means that data available over the Internet can be included, either continuously or after an event has been detected. This is another step towards the concept of near real time networks of networks of seismographs.

The earthquake preparation, alarm and response system has been tested by several events over the past year, including the ML 5.0 event at Thomson Reservoir in September 1996. Experience has indicated new features of value to clients can be included in the alarm and response reports, but the total size of the reports should be limited.

Paper No. 18

RECENT APPLICATIONS OF THE SEISMONITOR EARTHQUAKE PREPARATION, ALARM AND RESPONSE SYSTEMS

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1. INTRODUCTION

Figure 1 gives an overview of the elements involved in the earthquake preparation, alarm and response system developed by the Seismology Research Centre[1]. The system combines hazard information provided by the seismologist (earthquake location, magnitude and attenuation) with vulnerability information provided by the client (asset locations, vulnerability and importance, tasks and priorities).

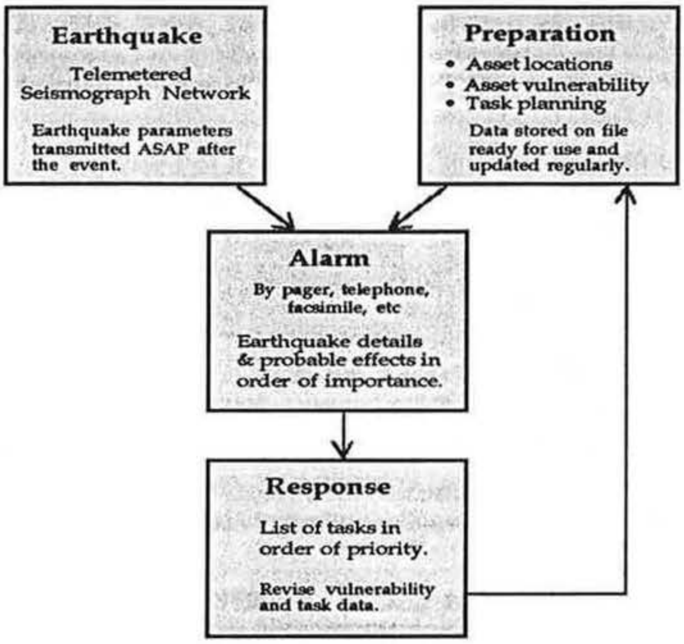

Figure 1: Overview of Elements of the system showing feedback loop.

The report generated by the system contains three sections:

The first describes the earthquake and the general outcomes of the earthquake, including descriptions of the expected effects likely to be observed in towns near the epicentre.

The second is specific to a particular authority. It contains descriptions, in order of importance, of the expected effects of the earthquake on a pre-determined list of assets for which the authority is responsible.

The final section comprises a list of tasks that should be undertaken by the staff of the authority, listed in priority order.

The alarm program calculates the modified Mercalli intensity for a given earthquake at each location in its data files. The program then looks at the tables of outcomes for each site and matches the calculated intensity to a text description for the general and specific outcomes likely to occur at that particular site for that intensity. It also matches the intensity at the site to a task data base for the authority to produce a list of tasks.

Data from the seismographs that make up the telemetered system are transmitted continuously to the SRC by radio, dedicated telephone line, or a combination of the two.

A recent development of the SeisMonitor program is the capability to incorporate time stamped data transmitted to the system via telemetry systems where the transmission time delay is unknown or unpredictable. For example seismic data available over the Internet can now be added to data recorded by a local network.

This stream of incoming data is fed to a dedicated earthquake detecting computer that digitally records any event that occurs, and alerts SRC staff of larger events via an automatic alphanumeric paging system at any time of the day or night. A rough preliminary location can be calculated by staff members from the information provided by the pager system (see below). In addition the stream of incoming data may be recorded at the centre on continuous analogue recorders so that a continuous real-time visual record of seismic activity within the network is always on hand.

For calculation of a reliable location and magnitude, it is necessary for one of the staff members with a portable computer and modem to dial into the SRC and download event data and perform a location on their portable computer. Alternatively a staff member can travel to the SRC office and locate the event. It is planned to have a real time earthquake location system automated, so that the pager system will also transmit a preliminary earthquake location and magnitude directly.

It is not expected that the earthquake alarm will be sent to users without verification by a seismologist, although some users may be interested in receiving a message to say that the alarm system has triggered on a major event and more details will be coming.

2. RECENT APPLICATIONS

1996 September 25, Thomson Reservoir, ML 5.0

An earthquake of magnitude ML 5.0 occurred at 05:49 pm on the evening of 1996 September 25 with its epicentre a few kilometres southeast of Mt Baw Baw.

The earthquake was preceded by a foreshock of magnitude ML 3.4 that occurred at the same place at 02:53 pm the same afternoon, and another magnitude ML 2.0 foreshock 63 seconds later.

The earthquake was felt in suburban Melbourne and throughout much of eastern and central Victoria. It was felt particularly strongly in the Mt Baw Baw area, where it was reported to have sounded like a large explosion, then the buildings shook strongly. Many small aftershocks occurred over the months following the earthquake, but because of the remote location few were felt.

The SeisMonitor system at the SRC laboratory triggered on both the foreshock and the mainshock. As the event happened close to normal working hours there were staff on hand at the laboratory who had located the foreshock and had informed the key client of that event. The key client was informed of the mainshock within minutes of it occurring.

The report generated by the Preparation, Alarm and Response system for the SRC nominated the most significant communication tasks to undertake and the general outcomes section broadly agreed with the isoseismal map depicted above.

Within hours of the mainshock the SRC began installing an aftershock network within the epicentral area. This network was augmented the next day with additional seismic recorders from the SRC and AGSO. The aftershock network comprised over 10 instruments at one stage.

1997 August 10, Collier Bay, MW 6.3

An earthquake of magnitude 6.3 occurred in Collier Bay in the Kimberley region of Western Australia on Sunday, August 10 at 05:20 pm WST. The epicentre was located 150 kilometres northeast of Derby, and 75 kilometres offshore from Koolan Island (124.3° east, 16.1° south).

Reports of it being felt were received from Broome to Kununurra. Some damage to concrete stumps of a single storey building occurred at Cockatoo Island, at a distance of about 75 kilometres. Modified Mercalli Intensity of 5 (strongly felt but no damage) was reported at Cape Leveque, about 150 kilometres from the epicentre.

The SRC SeisMonitor system is optimised to record earthquakes in southeastern Australia. However, the system does trigger on larger teleseisms, and for this earthquake sent the following pager message:

```
01: 1997-08-10 0926
CRN 19.2,00332,03.7
JBR 34.0,00085,08.4
WER 38.5,00068,06.7
AVO 41.0,00095,03.7
CDN ----,00062,06.6
TOM ----,00096,06.6
Group 4
19:32 10/8/97
```

The message gives in order the date and time of the trigger (in UTC) followed by information about the event as recorded at different sites in the format: Seismograph site code, number of seconds after the minute that the trigger occurred, peak counts for each channel and the maximum short term average over long term average ratio. Because the network of recorders used by the system is in southeastern Australia this event looked much like a teleseism and this event would usually have elicited no response from the SRC system. The SRC SeisMonitor system is optimised for southeast Australian earthquakes, and records a maximum duration of two minutes, so the S wave arrivals were not recorded for this event. A preliminary message was sent out by a staff member who happened to be at the laboratory.

```
02: Very large SHALLOW event,
probably Sunda Is or Banda Sea, GG
19:43 10/8/97
```

A revised message was sent after a preliminary location was determined. This location needed additional data from the Australian National Seismograph Network operated by AGSO, obtained using the Internet.

```
04: I make it MW 6 plus, about 200
km north of Derby, WA. It has been
felt Broome to Kununurra.
20:32 10/8/97
```

An aftershock network comprising four AGSO instruments was installed one week after the mainshock by AGSO and SRC personnel.

Because this event occurred so far outside the SRC seismograph network the Preparation Alarm and Response system identified no tasks.

1997 August 23, Mole Creek, ML 4.5

An earthquake of magnitude 4.5 occurred at 03:30 am on the morning of Saturday, August 24 with its epicentre near Mole Creek, 60 kilometres south of Devonport in Tasmania. It was recorded on seismographs operated by the RMIT Seismology Research Centre throughout Victoria and New South Wales.

This earthquake triggered the SRC SeisMonitor system which sent the following pager message:

```
02: 1997-08-23 1731
CDN 36.1,00244,05.7
TOM 36.5,00208,06.4
ROY 40.5,00542,06.4
GVL 41.9,00093,05.3
CRN 53.3,00244,06.1
DTM 55.8,00405,04.8
03:32 24/08/97
```

The duty seismologist determined that this was a local event requiring a response, dialled in to the laboratory and downloaded the waveform recorded by the SeisMonitor program before locating the event and sending the following pager message.

```
03:M? 4.5-5.0 70 km SW Launceston,
Tasmania.
04:26 24/08/97
```

Location of this event was difficult because it was well outside the SRC seismograph network. The Preparation, Alarm and Response system once again identified no further action to be taken for existing clients, because the event was so far outside the network. No aftershock network was installed.

3. CONCLUSION

A preparation alarm and response system has been developed to provide useful information to users regarding the likely effects of the earthquake, behaviour of various assets and the appropriate actions to take following a significant earthquake.

The system has proved useful for large events within the seismograph network but is difficult to use and has limited accuracy for events well outside the network.

For a rapid and precise location of an earthquake, a network of recorders surrounding the epicentre is required. It would be possible to minimise this limitation by linking a number of SeisMonitor systems over the Internet. Each sub network could broadcast its triggers to the other systems giving them access to a wider network of seismograph data and leading to a large network of independent sub-networks of seismographs.

The Preparation, Alarm and Response system is dependent upon the quality of the data input from both the seismograph network side and the database side (see figure 1). For a useful calculation of the effects and tasks to be carried out, a complete database of assets and vulnerabilities is required. However, care must be taken to minimise the size of the reports generated, and to include only significant information.

At present the SeisMonitor system is not autonomous. It requires trained and experienced personnel who are aware of its limitations, and are capable of making informed decisions regarding the actions to be carried out following the occurrence of a large earthquake.

Reference

1. Peck, W., Gibson, G. and McPherson, G. (1996). "Earthquake Warning, Alarm and Response Systems" *Proc. AEES seminar 1996*. Adelaide.

MICROTREMOR SURVEY OF ADELAIDE

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AUTHORS:

ABSTRACT:

A seismic microzonation of the Adelaide City Council area has been carried out using the microtremor method. Recordings were taken at 106 sites and mean horizontal versus vertical spectral ratios plotted. A geometric mean was calculated over 3 frequency ranges to emulate high rise, medium rise, and low rise building ranges. Over most of the city a strong low frequency (1Hz) peak is evident. This is contrary to what was expected. It has generally been assumed that Adelaide would experience some, probably limited, high frequency amplification due to sediments above the very stiff Hindmarsh Clay. However further investigation reveals that there is a considerable depth of weaker materials underneath, which is probably responsible. This result would explain why high rise buildings experience movement from large distant events such as Tennant Creek and Indonesia. A microtremor reading taken while a train was passing shows that moderate and weak motion give similar spectral ratio results.

Paper No. 19

INTRODUCTION

A GIS containing information relating to earthquake risk has been produced for the SA State Emergency Services by Mines and Energy Resources SA and the Australian Geological Survey Organisation. The project was carried out in 1996-7 with funding from Emergency Management Australia as part of the IDNDR program. The field work constituted a microtremor survey of 106 sites over the Adelaide city, North Adelaide and parklands area. The microtremor method is now commonly being used across Australia [1][2].

METHOD

Four readings, each of about one minute were taken at each site, with a 1 Hz three axis seismometer and digital recorder. The equipment was set up in the back of a vehicle, and field work progressed at the rate of about 3 sites per hour. In processing an attempt was made to select time segments with the lowest noise level, however the presence of much higher noise levels did not seem to affect the results significantly. Data reduction is described by Nakamura [3]. As an extension of the method, the geometric mean of three frequency ranges were calculated, plotted and contoured to represent the likelihood of resonance affecting high rise (0.015 - 1.5 Hz), medium rise (1.25 - 3.75 Hz) and low rise (3 - 10 Hz) structures.

RESULTS

As most of the Adelaide metropolitan area, particularly this project area, is underlain at shallow depth by the Hindmarsh clay (stiff to hard consistency[4]), it was assumed that much of the area would be affected by high frequency resonance. This however was not the case and the most outstanding result of the exercise was the discovery of a pervasive low frequency peak (usually at a maximum around 1 Hz) for most of the area. Most spectral ratio plots had a peak in the 0.5 to 2 Hz range, with or without a broad secondary peak in the 4 to 8 Hz range (Figure 1).

Out of 106 sites, only 13 gave values over 2 for the low rise resonance coefficient. Only 15 were over 2 for the medium rise resonance coefficient. For the high rise coefficient only 2 sites had values under 2, most of the area was over 4, with 15 readings over 6. The area containing the lowest values happens to coincide with a significant proportion of Adelaide's high rise buildings near the King William St, North Tce intersection.

There were a few different spectral ratios, the most outstanding being one on the edge of North Adelaide, which gave three clear peaks, but significantly different response in the east-west and north-south directions (Figure 2). It is possible that other sites may have shown this effect if the seismometer had been oriented differently.

DISCUSSION

The contouring of the building height coefficient was generally successful, although some sites did appear to be "bull's eyes". It is assumed that with more detailed spacing a gradation would be revealed. It is also uncertain to what level there may be contamination of low frequency data by reading too near very tall buildings. Only one peak in Adelaide city may have been affected.

The low frequency peak is a probable explanation for a well known, but surprising phenomemon of large distant earthquakes being felt in high rise buildings in Adelaide. Earthquakes in Indonesia have been felt on a number of occasions and it is believed that

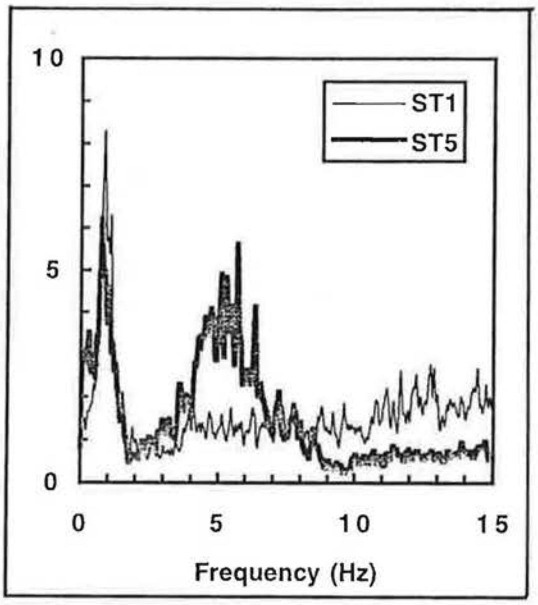

Fig 1. Characteristic Spectral ratios

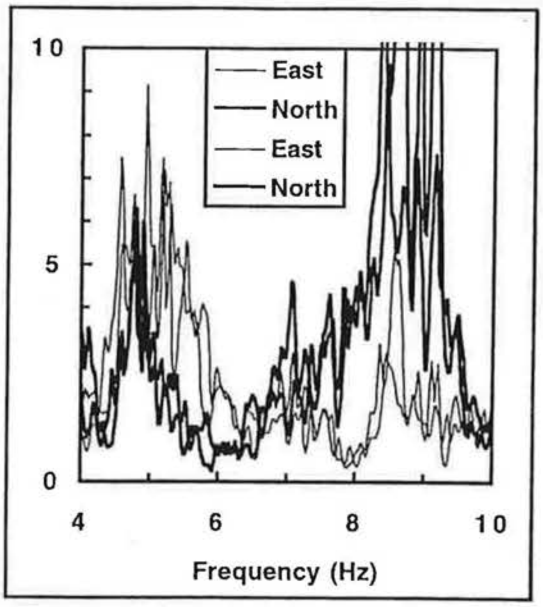

Fig 2. Polarised spectral variation

on one or more of these a building has been partly evacuated. The Tennant Creek earthquakes of 1988 were felt by about 40 percent of the high rise buildings in the city. The source of the low frequency is uncertain at present, but is clearly caused by properties at considerable depth.

THE GIS PACKAGE

The ArcView software package was chosen as the final format for data presentation, due to its moderate cost, availability on Unix, PC and Macintosh, relative ease of learning, and wide capabilities. It is also a companion product to the larger ArcInfo package, which is used at both MESA and AGSO.

Other data sets included with the spectral ratios and building coefficient contours were: an airphoto image, building footprint and height, the cadastre, gas, electricity and water, and surface contours and drainage. Figure 3 shows a gray scale image of the project area, overlain by microtremor sites and high rise coefficient contours.

CONCLUSION

The relative speed of the microtremor method and ease of processing makes this a useful method to investigate earthquake hazard. It responds to velocity variations occurring in the volume under the site, both near surface and at depth, at a much lower cost than drilling. It is expected that such data packages will become standard tools for the assessment of earthquake risk in Australia.

Fig 3. Microtremor sites and high rise coefficient contours with air photo backdrop

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EARTHQUAKE SITE AMPLIFICATION IN THE CAIRNS REGION ESTIMATED FROM MICROTREMOR RECORDINGS

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ABSTRACT:

In early 1997 microtremor recordings were conducted at approximately four hundred sites in the region from Gordonvale in the south to Palm Cove in the north, including Cairns city proper (the greater Cairns region). This work was conducted by personnel of the Queensland University Advanced Centre for Earthquake Studies (QUAKES) and the Australian Geological Survey Organisation (AGSO) as part of the AGSO's Geohazards Vulnerability of Urban Communities project (AGSO'S Cities Project). The purpose of these recordings was to estimate where geological structure may amplify potential earthquake ground motion and determine the frequency of this amplification. Results show that amplification occurs at locations in the Cairns region underlain by Quaternary sediments. The peak amplification frequency generally correlate with the expected thickness of the Quaternary sediments, with amplification at higher frequencies on thin sedimentary cover and lower frequencies in regions underlain by thicker sediments. Results from supercomputer simulations suggest the microtremor method works best when the underlying geology is simple and may mispredict the frequency of amplification by as much as 10%.

1 Introduction

In late February and early March of 1997, the Queensland University Advanced Centre for Earthquake Studies (QUAKES) and the Australian Geological Survey Organization (AGSO) conducted fieldwork to record microtremors (background earth motion) in and around Cairns, Queensland. This work was conducted as part of a collaborative effort between QUAKES' Australian Research Council funded regional earthquake hazard program and AGSO's Geohazards Vulnerability of Urban Communities project (the 'Cities Project'). The purpose of these recording were to estimate where the underlying geology in the Cairns region may amplify ground motion, and to determine the fundamental resonant frequency of this amplification.

2 Data Collection

The data collection was carried out by QUAKES and AGSO personnel, divided into three teams of two people each. We used QUAKES' Guralp CMG-40T three-component velocity sensors with Kelunji D-series seismic recorders. The CMG-40T sensors have a response that is flat to ground velocity in the frequency band from 0.03 to 50 Hz. Two hundred seconds of background earth motion were recorded at each site. Recording were carried out at a nominal 500 metre spacing in the densely populated parts of the Cairns region, with wider spacing in the agricultural regions. Recordings were taken at a total of 409 sites.

3 Data Analysis

The data were analyzed using a procedure developed by Nakamura[1]. In this method the amplitude spectra of the horizontal ground motion are divided by the spectrum of the vertical ground motion. In the presence of geological amplification of ground motion, the resulting spectral ratio will show a peak(s) near the fundamental frequency of vibration of the amplification.

We calculated spectral ratios using five slightly overlapping windows of 40.96 seconds of recorded ground motion. This results in ten individual spectral ratios (i.e., five East-West/Vertical and five North-South/Vertical ratios). In some cases the ground motion recording was short due to technical problems, etc., and therefore fewer windows were used. The ground motion data were detrended and tapered with a 5% cosine taper prior to calculating the spectra. The resulting spectra were smoothed twice with a 5 point moving boxcar smoothing operator.

The ten resulting spectral ratios were averaged to get a mean spectral ratio. Both the mean spectral ratio and the ten contributing ratios were plotted together. The spectral ratios were given a quality rating ranging from A (best) to D (worst) dependent upon the stability of the spectral ratio estimate.

4 Results

In many cases the spectral ratios show clear amplification of the horizontal ground motion relative to the vertical ground motion, as evidenced by peaks in the spectral ratio. Some of the peaks are narrowly centered at particular frequencies while other peaks are distributed across a range of frequencies. In each of these cases both the range of amplification frequencies and the median frequency of amplification were estimated.

In several cases the resulting spectral ratios showed no evidence of spectral peaks. These sites were classified as "No resonant effects". We also found that for several sites the spectral ratios simply increased monotonically at low fequencies. Since no clear peak in the spectral ratio could be found, these sites were give a D quality rating and not used in the interpretation of the results.

The spectral ratio results were plotted on a map of the Cairns region and compared with the geology. Only A and B quality spectral ratios were used in the initial interpretation; inclusion of C quality spectral ratios did not significantly change the results. Therefore results using A, B, and C quality spectral ratios are presented here.

Figure 1 shows the results of the microtremor survey. In the Northern Beaches subregion (Figure 1a), the amplification frequencies correspond well with the underlying geology. Amplifications at less than 2 Hz occur primarily on the Quaternary sediments of the Barron River floodplain and along Clifton Beach. North and west of the Barron River floodplain the amplification frequencies increase, consistent with decreasing thicknesses of young sediments. "No resonant effects" sites are generally found along the front of the McAllister Range, where sediment is expected to be either very thin or absent. Note, however, that there are some discrepancies: a site showing no apparent amplification occurs in Machans Beach, in the midst of other sites showing amplification at low frequencies.

The amplification frequencies also correspond well with the underlying geology in the Cairns City subregion (Figure 1b). Much of Cairns City is underlain by Quaternary beach and estuarine deposits, and correspondingly shows amplifications at very low frequencies (with one exception, i.e., a site near Trinity Inlet). As one moves north and west towards the slopes of Mt Whitfield and the Whitfield Range the amplification frequencies get higher, as would be expected as the thickness of the young sediments decreases. Sites showing no amplification or amplification at very high frequencies are encountered on the slopes of Mt Whitfield and the Whitfield Range, consistent with very thin or absence of sedimentary deposits. Results showing greater variation are seen west of the Whitfield Range in Freshwater Creek Valley and at the mouth of the Barron River Gorge. This suggests rapid variations in sediment thicknesses in these areas. The frequency of amplification generally gets higher as one goes south of Cairns City along the Bruce Highway, suggesting decreasing sediment thicknesses.

Data recover in the Edmonton-Gordonvale subregion (Figure 1c) was poor (i.e., many D quality spectral ratios), making interpretation more difficult. Spectral ratio peaks at lower frequencies (< 4 Hz) are encountered in north Edmonton, suggesting relatively thick Quaternary deposits. A variety of spectral ratio frequency peaks and sites showing no resonance are encountered in central and southern Edmonton, suggesting rapid variation in sediment thickness. Results from Gordonvale are more consistent, with peaks at low frequencies in north and southeast Gordonvale and higher frequencies and "no resonance" sites to the south and west.

5 Discussion

While Nakamura's method has been shown to be successful in revealing the fundamental frequency of ground motion amplification, both field[2,3] and numerical simulation studies[4,5] show that it does not generally reveal the frequencies of higher mode amplifications, nor does the amplification magnitude correlate well with amplification magnitudes observed during actual earthquake shaking[2,3]. In addition, recent results from supercomputer simulations show that site amplification can be very dependent upon the two- and three-dimensional geologic structure of a region and the angle of the incoming seismic waves[6]. In some cases the frequency of the strongest amplification can be very different from that revealed by Nakamura's method.

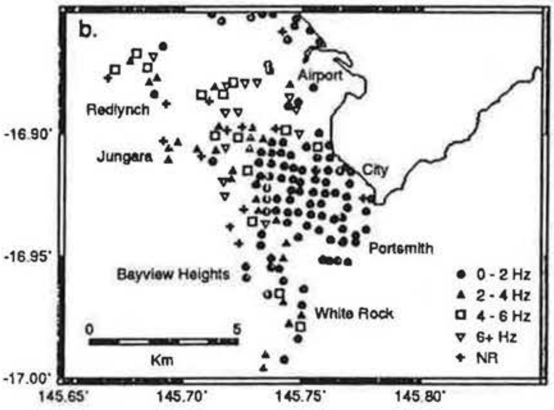
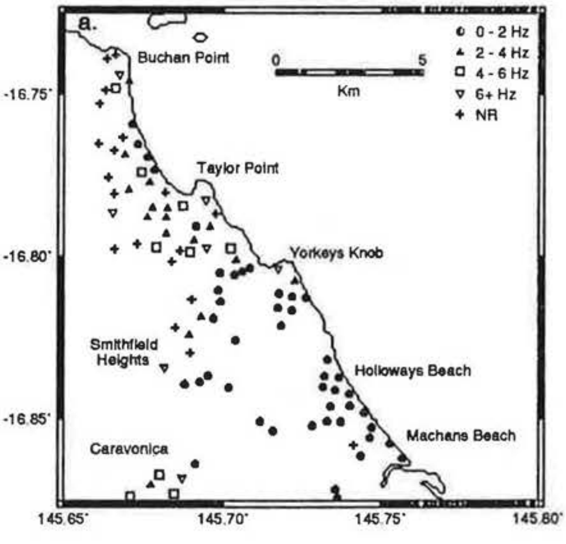
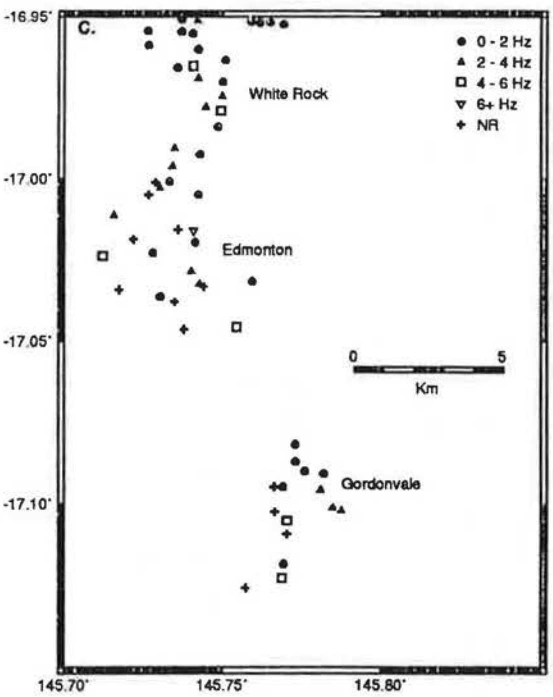


Figure 1: Results of the microtremor survey for different subregions of the greater Cairns area: (a) Northern Beaches, (b) Cairns City, and (c) Edmonton-Gordonvale. The symbols are grouped together according to the median frequency of amplification; NR stands for "No resonant effects". Only those sites with A, B or C quality ratings are used.





For the reasons cited above, caution is needed in interpreting the results of this study. The clear spectral peaks at many sites show that the geology underlying much of the Cairns region will act to amplify the ground motion during an earthquake. While amplification will likely occur at or near the fundamental frequency of vibration estimated by Nakamura's method, the magnitude of this amplification is not well known, nor is it known whether there will be even greater amplification at higher frequencies. Thus, this study provides useful but limited information on the amplification of earthquake ground motion in the Cairns region.

6 Conclusions

A microtremor survey of the greater Cairns region was conducted in late February and early March of 1997 by QUAKES and AGSO. Analysis of the microtremor data reveals that the local geology acts to amplify ground motion in much of the Cairns region. In particular, ground motion amplification occurs at frequencies of less than 2 Hz in the Barron River floodplain and Cairns City, consistent with the significant thicknesses of young sediment believed to underlie these regions. The frequencies at which amplification occurs increase as one approaches the mountain ranges to the west, consistent with decreasing sediment thicknesses. The microtremor methodology is valuable but is known to have limitations and ongoing work is required to reliably quantify the amplitude and frequencies of ground motion amplification.

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