ASEISMIC DESIGN AND CONSTRUCTION OF EARTH BUILDINGS IN NEW ZEALAND

Hugh W MORRIS[1] And Richard WALKER[2]

SUMMARY

New Zealand is in an area of high seismicity and has a strongly regulated construction environment. Design and construction standards for earth buildings were developed to satisfy the national building code. The performance based standards are primarily intended for houses and low rise buildings made of adobe, rammed earth, pressed earth brick and similar earth building materials

Design methodologies were adapted from existing masonry and concrete standards using limit state design principles. An energy method was chosen for out-of-plane seismic design.

A number of simple low cost material test procedures are defined in the standards and construction details based on current best practice are provided. To confirm structural strengths, some material tests and structural tests of several near full scale earth wall panels were carried out using the recommended details.

The New Zealand standards will provide a basis for the development of similar standards in other seismically active countries.

INTRODUCTION

Earthquake Hazards in New Zealand

New Zealand is in an area of high seismicity, particularly the northern part of the South Island and the central, eastern and southern parts of the North Island.

Large earthquakes in the last 100 years include both the 1929 Murchison earthquake, Richter magnitude M7.8 and the M7.4 Inangahua earthquake in 1968 at the north of the South Island. The intensity on the Modified Mercalli (MM) scale for New Zealand was assessed at MM IX at Murchison during the 1929 earthquake. In 1931 the other major event M7.9 intensity MM X occurred on the East Coast of the North Island. This had devastating effects for Napier leading to New Zealand introducing lateral load requirements to improve the earthquake performance of buildings.

The mean return period for MM IX intensity was estimated [Smith and Berryman 1992], to be between 300 and 500 years for the northern part of the South Island and southern part of North Island. The mean return period for MMVIII earthquake shaking has been estimated to be less than 100 years for the same area.

Earth Building Construction in New Zealand

Earth building began in New Zealand in the early part of the last century. Approximately 120 earth houses still exist that were constructed between 1840 and 1870 and a further 170 exist from 1870 to 1910. The growing

[1] *The University of Auckland*
[2] *Consulting Engineer*

interest in more environmentally friendly and sustainable buildings has led to an upsurge of earth building construction and well over 100 earth buildings have been built during the past 10 years. [Allen 1997] In some areas of New Zealand over one percent of new houses are constructed with earth.

A notable example of an earth building that has survived three major earthquakes (MMVII or greater) is Broadgreen House near Nelson in the upper South Island which was constructed in the 1850s. The apparent factors that account for the good performance of this large two storey cob building were: the low height to thickness ratio of the earth walls, the relatively few openings, sufficient earth bracing walls in each direction, the first floor acting as a structural diaphragm, and relatively good quality earth wall construction. The 500 mm thick earth walls of the ground floor reach 2700mm to the first floor giving a height to thickness ratio of 5.4 which complies with present design criteria for unreinforced earth walls in New Zealand.

The main forms of earth construction at present in New Zealand are adobe, rammed earth and pressed brick. Adobe and cob are the most common types of older earth buildings still existing today. Cob construction involves placing a puddled earth mix directly into place in walls without the use of formwork or mortar.

Adobe construction utilises air-dried "mud bricks" made from a puddled earth mix cast into a mould. The earth mix contains sand, silt and clay and sometimes straw or a stabiliser which is also used to mortar the walls. Both unstabilised adobe and adobe stabilised with cement are used in New Zealand.

Rammed earth comprises monolithic wall panels constructed with damp well graded sandy soils compacted in 100 to 150 mm thick layers between temporary movable formwork. In New Zealand the soils are usually stabilised with 5 to 10 percent cement. Pressed bricks use similar soils to rammed earth and are formed in a mechanical press which is either hand or machine operated. Pressed bricks are usually laid with sand-cement mortars.

New Zealand Building Legislation

Construction in New Zealand is governed by the *Building Act* [Building Act 1991] which established a framework of building controls with the *Building Regulations* [Building Regulations 1992] containing the mandatory New Zealand Building Code. Approved Documents provide methods of compliance with the Building Code and may cite documents such as the New Zealand Standards as a way to comply with the Code.

About 90% of New Zealand housing is timber so approved document NZS 3604 *Code of Practice for Timber Framed Buildings not requiring specific design* [Standards New Zealand 1978] established the precedent for this type of document. *NZS 3604 Timber Framed Buildings* [Standards New Zealand 1999] is now 400 pages with numerous tables and well drawn diagrams that allow builders and architectural draftspeople to design houses to resist earthquake and wind loads.

EARTH BUILDING STANDARDS

Existing International Standards

Some countries such as USA, China, Peru and Turkey have existing earth building standards. These are generally brief prescriptive documents giving guidelines regarding structural form and materials and include some provisions for improving the earthquake resistance of earth buildings.

Bulletin 5 Earth Wall Construction [National Building Technology Centre 1987] is the defacto standard for earth construction in Australia and is accepted by many local authorities. There are no provisions for earthquake loads in Bulletin 5.

Development of New Zealand Earth Building Standards

To cater for the growing interest in earth building in New Zealand three substantial and comprehensive performance based standards for earth walled buildings were published in 1998. The standards were prepared by a joint technical committee of engineers, architects, researchers and builders and were developed over a period of 7 years from earlier guideline documents by the Earth Building Association of New Zealand and Gary Hodder [Hodder 1991]. In the early stages there was considerable input from Australian earth building practitioners.

These new standards, as described below, formalise the current state-of-the-art for the design and construction of earth buildings in New Zealand and are intended to be approved as a means of compliance with the New Zealand Building Code.

Engineering Design of Earth Buildings

NZS 4297 Engineering Design of Earth Buildings [Standards New Zealand 1998] specifies design criteria, methodologies and performance aspects for earth wall buildings and is intended for use by structural engineers.

Limit-state design principles were used in the formulation of this standard to be consistent with other material design standards. Earthquake loads are more critical than wind loads for most earth buildings in New Zealand and earth wall heights are limited to 6.5 m in this standard. The design methodologies are discussed in more detail later in this paper.

Materials and Workmanship for Earth Buildings

NZS 4298 Materials and Workmanship for Earth Buildings [Standards New Zealand 1998] defines the material and workmanship requirements to produce earth walls which, when designed in accordance with NZS 4297 or NZS 4299, will comply with the requirements of the New Zealand Building Code. Requirements are given for all forms of earth construction but more specifically for adobe, rammed earth and pressed brick.

Earth buildings are often constructed with local soils from near the building site and detailed laboratory test results are seldom available for a building project. The suite of standards is primarily intended for small-scale construction so a number of simple low cost test procedures are defined in the Materials and Workmanship standard. This testing can be done by the person responsible for the construction of the building in the presence of the owners or the controlling building authority as required.

Compression or modulus-of-rupture tests are specified for determining the strength requirements of the earth wall materials. Compression tests need to be done in a laboratory but two simple test procedures are detailed for the modulus-of-rupture test and a brick drop test is specified for simple field testing of earth bricks.

Two grades of earth wall material are covered within the standard:

- Standard Grade with a design compressive strength of 0.5 Mpa which can be obtained by low strength materials with a minimal amount of testing, or
- Special Grade which requires more testing to reasonably predict the characteristic strength. Earth stabilised with cement may achieve strengths of up to 10 Mpa. More complex engineered structures would be of Special Grade.

Standard grade strengths are similar to those specified for adobe bricks in the *New Mexico Building Code 1991*.

Earth Buildings Not Requiring Specific Design

NZS 4299 Earth Buildings Not Requiring Specific Design [Standards New Zealand 1998] provides methods and details for the design and construction of earth walled buildings not requiring specific engineering design. The main users of the document will be designing houses but will include a range of people in the earth building industry including builders, architects, engineers, students and building authority staff.

This standard covers buildings with single storey earth walls and a timber framed roof, or single lower storey earth walls with timber second storey walls and a light timber framed roof. The scope is limited to footings, floor slabs, earth walls, bond beams and structural diaphragms. The design of the timber roof structure would be covered by NZS3604 *Timber Framed Buildings* [Standards New Zealand 1999] or specific engineering design.

NZS 4299 Earth Buildings Not Requiring Specific Design is the earth wall construction equivalent of NZS 3604 with similar methodology. It is intended to provide a means of compliance with the New Zealand Building Code.

Earth buildings covered by this standard resist horizontal wind and earthquake loads by load bearing earth bracing walls that act in-plane in each of the two principal directions of the building. A simple design methodology and detailed tables in terms of “bracing units” are provided in the standard for determining the “bracing demand” required for the building and the “bracing capacity” provided by the nominated bracing walls.

Many construction details which have been proved in earth buildings constructed in New Zealand during the past 12 years are included in the standard. Specific examples are given in the Aseismic Construction Details section.

ASEISMIC DESIGN METHODOLOGIES

Design Approach

Design methodologies for earth buildings in New Zealand have been adapted from existing masonry and concrete standards. The design approach in the standards is based on simple ultimate strength reinforced concrete theory and uses limit state design principles for both elastic and limited ductile response. The structural ductility factor was taken as 2.0 for reinforced earth walls, 1.25 for the narrower cinva brick walls, and 1.0 for unreinforced and partially reinforced earth walls.

In *NZS 4299 Earth Buildings not Requiring Specific Design*, the earth walls were designed as spanning between the reinforced concrete foundation at the bottom of the wall and the top plate or bond beam at the top of the wall. Loads from the tops of walls, roofs and timber second storeys were assumed to be distributed by concrete or timber bond beams or structural ceiling or roof or first floor diaphragms to transverse earth bracing walls.

The seismic coefficients for the design of the earth walls were as follows:

- Unreinforced earth walls with elastic response for earthquake zone factor ≤ 0.6, C = 0.322
- Reinforced earth walls with limited ductility for earthquake zone factor ≤ 0.6, C = 0.197
- Reinforced earth walls with limited ductility for earthquake zone factor > 0.6, C = 0.394

Earthquake Zones

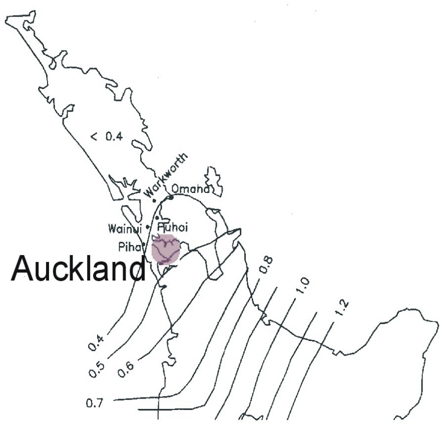

FIGURE 1 Seismic Zone Factor, Z for upper North Island

The earthquake zone factors used for the design of earth buildings are in accordance with *NZS 4203 General Structural Design and Design Loadings for Buildings* [Standards New Zealand 1992] except for the Auckland area and north of Auckland. Because of the height limitation in the earth building standards the earthquake zone factor is reduced to 0.4 for Northland. This more accurately reflects the hazard as mapped by seismologists [Dowrick 1992] which was artificially restricted to 0.6 in NZS 4203 to minimise risk and limit damage in the event of a serious earthquake in Auckland

In *NZS 4299 Earth Buildings not Requiring Specific Design* two earthquake zones with the following factors were adopted for the determination of seismic loads. For earthquake zone factor ≤ 0.6 the value Z = 0.6 was adopted and for earthquake zone factor >0.6 the value Z = 1.2. All earth walls for earthquake zone factor ≤ 0.6 may be reinforced or unreinforced. All earth walls in earthquake zone factor > 0.6 shall be reinforced.

This latter zone includes most of New Zealand except for the north-western part of North Island and the south-eastern part of South Island.

Specific engineering design is required for unreinforced earth walls in earthquake zone factor > 0.6

Strength

The following strengths are used for the design of standard grade earth wall construction:

- Compressive strength (flexural, direct compression or bearing) 0.50 Mpa
- Shear strength of earth for limited ductile seismic loading 0.00 Mpa
- Shear strength of earth for seismic loading with elastic response 0.08 Mpa
- Flexural tensile strength 0.10 Mpa

Higher strengths may be used for special grade construction and these are determined using the test methods in the Materials and Workmanship standard.

Out-of-Plane Loads

Ultimate strength reinforced concrete theory is used for designing reinforced earth walls. Generally vertical reinforcing supports reinforced earth wall panels against out-of-plane face loading.

An energy method is used for assessing the ultimate limit state seismic out-of-plane resistance of walls spanning vertically. Elastic design would be based on strength at first cracking. The energy approach is based on the collapse mechanism when the displacement of the wall moves beyond stability. The method is the same as that prescribed in *Assessment and Improvement of the Structural Performance of Earthquake Risk*. [New Zealand Society for Earthquake Engineering 1996]

Using the energy method, unreinforced earth walls for earthquake zone factor ≤ 0.6 were found to be satisfactory for the maximum wall heights permitted in the standard. For example the failure of a 2700 mm high and 280mm thick wall was calculated to occur at 178 % of the calculated demand requirement with $\phi \leq 0.6$.

In-Plane Loads

Earth bracing walls provide seismic load resistance in each principal direction of the building. Reinforced earth walls are reinforced vertically and horizontally to provide some in plane ductility and to increase shear strength.

The reinforcement enables smaller seismic design loads, when a planned ductile failure mode is designed for the structure. The designed failure mode is in-plane bending of the earth bracing walls with yielding of vertical reinforcing at each end of the wall. Shear failure of these walls is prevented typically by the use of well distributed horizontal reinforcing. Vertical reinforcement is kept to a reasonable minimum to limit in plane shear loads and foundation forces.

Unreinforced walls provide considerably less bracing capacity without the vertical and horizontal reinforcement. Shear failure is prevented solely by the shear strength of the earth.

The maximum bracing capacity provided by a reinforced earth wall, 2400 mm long, 2400 mm high and 280 mm thick with typical details in accordance with the standard, see Figure 3, was calculated to be 30 kN. The bracing capacity provided by a similar sized unreinforced earth wall for earthquake zone factor ≤ 0.6 was calculated to be 10 kN.

Wall Height to Thickness Ratios

Unreinforced walls are restricted to 3.3 m height and the maximum height to thickness ratios are as follows:

Table 1

Earthquake zone factor	**Z ≤0.6**	**Z > 0.6**
Unreinforced load bearing wall	10	6
Reinforced load bearing wall	16	10
Unreinforced non-load bearing wall	12	8
Reinforced non load-bearing wall	18	12
Reinforced cinva brick	24	16

ASEISMIC CONSTRUCTION DETAILS

Reinforced Walls

Reinforced earth walls constructed in accordance with NZS 4299 have one D12 vertical reinforcing bar at each end of a bracing wall at a distance of 150 to 200 mm from the ends of the bracing wall as shown in Figure 3.

Additional vertical reinforcing is provided in longer walls as required to resist out of plane face loads. For example the average spacing of vertical reinforcement required for a 2400 mm high wall is 1650 mm

Horizontal reinforcing is required for reinforced earth walls with several alternatives given in the standard. In mortar joints these include either 5.3 mm diameter wire (cut from 665 steel mesh reinforcing) with 100 mm cross wires at 450 mm centres vertically, or polypropylene biaxial geogrid cut into 200 mm wide strips also at 450 mm centres. Details of the geogrid option are shown in Figure 2.

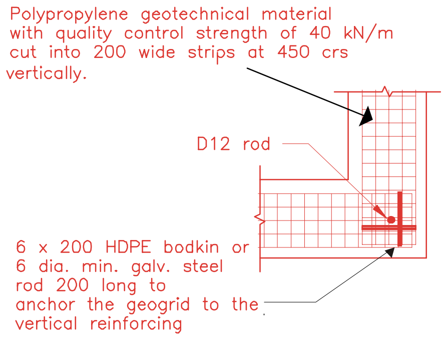

FIGURE 2 Detail of Geogrid Horizontal Reinforcement for Reinforced Walls

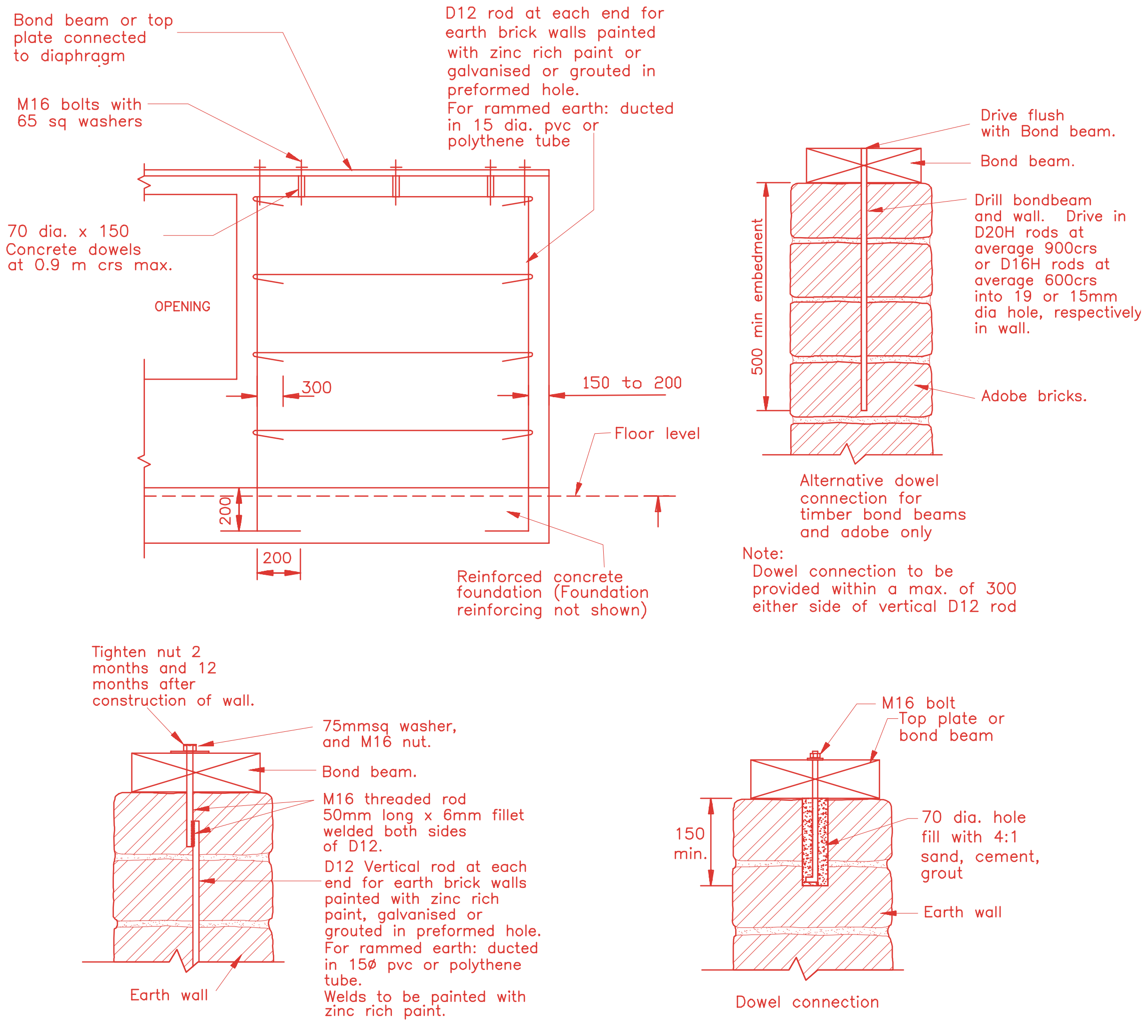

FIGURE 3 Reinforcing and Dowel Connections for Reinforced Walls

Partially Reinforced Walls

Partially reinforced earth walls are often a more practical and cost effective alternative than unreinforced earth walls in earthquake zone ≤ 0.6. They have a vertical D12 bar at each end of the wall similar to a reinforced wall but do not have any additional vertical or horizontal reinforcing. The bracing capacity provided by a partially reinforced wall is two to three times greater than an unreinforced wall.

Unreinforced Walls

Only unreinforced earthwalls in earthquake zone ≤ 0.6 are within the scope of NZS 4299. Dowels as shown on Figure 3 are required at the tops of walls to transfer shear loads from the top plate and roof or ceiling or floor structural diaphragm to the earth wall.

Structural Diaphragms and Bond Beams

NZS 4299 details requirements for structural diaphragms and these can comprise diagonal sarking, sheet sarking of plywood or high density internal ceiling plaster board or sheet flooring of plywood or wood based product over 17 mm thick. The connections between the tops of the earth walls and the structural diaphragms are detailed. Typically these include solid blocking between the rafters or joists and metal nailon plates.

Bond beams at the tops of the walls may be either timber or reinforced concrete. Timber bond beams in earthquake zone >0.6 are to be used only in conjunction with structural diaphragms. Timber bond beams in earthquake zone ≤ 0.6 may be used without structural diaphragms but must be continuous between cross walls.

STRUCTURAL TESTING

A series of tests investigated the performance of soil cement materials followed by 1.2m adobe wall panel tests with differing reinforcement regimes. [Gurumo 1992] Using a test layout similar to figure 4, several near full-scale adobe walls were tested in-plane. Figure 5 shows how slipping in the mortar planes gave effective ductility in a wall with both horizontal and vertical reinforcing [Morris 1992].

Several rammed earth walls 1.8m wide and 2.4m high were tested, the first gave an equivalent shear stress of 241kPa before the base of the test system delaminated. A later test 2.4m high and 1.8m wide was reinforced vertically at each end and performed as shown in figure 6 with a maximum load of 90kN an equivalent horizontal shear of 143kPa [Walker and Morris 1998].

Adobe walls behave in a ductile manner but are low strength requiring most walls to be available for bracing strength. Rammed earth reaches much higher strengths but requires reinforcement to prevent brittle failure.

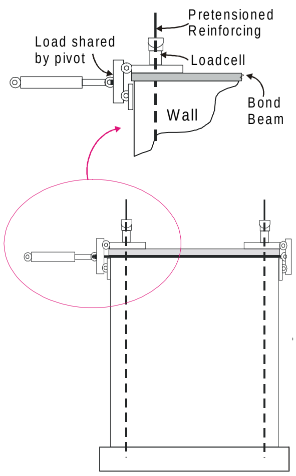

FIGURE 4 Load configuration for in-plane panel tests

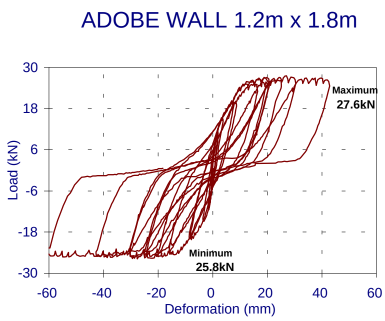

FIGURE 5 Horizontal Deformation of 1.2m Wide 1.8m Tall Adobe Panel under Cyclic Loading

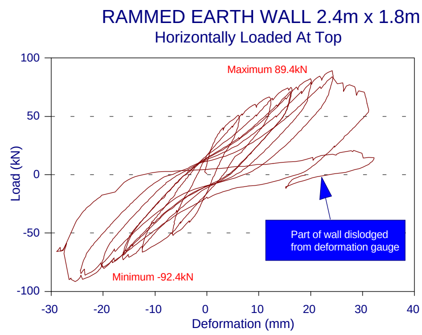

FIGURE 6 Horizontal Deformation of 2.4m Tall Rammed Earth Panel under Cyclic Loading

CONCLUSIONS

A systematic and performance based approach to aseismic design of earth buildings has been developed and is backed up structural testing of near full scale earth wall panels.

The New Zealand Earth Building Standards formalise this performance-based approach and the current state-of–the-art for the design and construction of earth buildings. These standards have enabled earth building to become a mainstream building material in a seismically active country with strict building regulation and will provide the basis for development of similar standards in other seismically active countries

ACKNOWLEDGEMENTS

The authors acknowledge the enormous amount of work done by other members of the voluntary technical committee of engineers, architects, builders and researchers from New Zealand and Australia in development of the earth building standards, and Ian Brewer a Standards Development Consultant for Standards New Zealand.

Assistance and sponsorship for the development of the standards was provided by Standards New Zealand, the Earth Building Association of New Zealand (EBANZ) and the Institution of Professional Engineers (IPENZ). Figures 1, 2 and 3 are used with the kind permission of Standards New Zealand.

REFERENCES

Allen, Miles, 1997, *Out of the Ground - Earthbuilding in New Zealand*, Dunmore Press, Palmerston North, ISBN 0 86469 290 9

Building Act 1991, Department of Internal Affairs, Wellington, New Zealand.

Building Regulations 1992, Department of Internal Affairs, Wellington, New Zealand.

Dowrick, David J., 1992, "Seismic Hazard estimates for the Auckland Area, and their Design and Construction Implications", *Bulletin of the New Zealand Society for Earthquake Engineering*, Vol.25, No.3, pp 211-221.

Gurumo, Shabani R, 1992, *Diagonal Compression Strength of Adobe Wall Panels*, Master of Engineering Project D Report, The University of Auckland,(unpublished).

Hodder, Gary, 1991, *Earth Building Non Specific Design Guidelines*, Published by Gary Hodder Consulting Registered Engineer, Nelson, NZ.

Middleton, George F., revised Schneider, Lawrence M., 1987, *Bulletin 5 Earth-Wall Construction*, 4th Edition, National Building Technology Centre, ISBN 0-642-12289-X.

Morris Hugh W., *The Strength of Engineered Earth Buildings*, Preceedings, IPENZ Annual Conference, Sustainable Development, Hamilton, February 1993, Pages 660-671

New Zealand National Society for Earthquake Engineering, 1996, The Assessment and Improvement of the Structural Performance of Earthquake Risk Buildings.

Smith, Warwick D. and Berryman, Kelvin R., 1992, *Earthquake Hazard Estimates for New Zealand: Aspects of Changes in the Seismicity Model*, DSIR contract report.

Standards New Zealand, 1978, NZS *3604 Code of Practice for TIMBER FRAMED BUILDINGS not requiring specific design*.

Standards New Zealand, 1992, NZS *4203 Code of practice for GENERAL STRUCTURAL DESIGN AND LOADINGS FOR BUILDINGS*.

Standards New Zealand, 1998, NZS 4297, *Engineering Design of Earth Buildings.*

Standards New Zealand, 1998, NZS 4298, *Materials and Workmanship for Earth Buildings*.

Standards New Zealand, 1998, NZS 4299, *Earth Buildings not Requiring Specific Design*.

Standards New Zealand, 1999, NZS *3604 Timber Framed Buildings*.

Walker Richard and Morris Hugh W., 1998, "Development of New Performance Based Standards for Earth Building", *Australasian Structural Engineering Conference, Proceedings Vol. 1* pp477-484.