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Base isolation of low rise light and medium-weight buildings

SJ Thurston

The work reported here was jointly funded by Building Research Levy, the Foundation for Research, Science and Technology from the Public Good Science Fund, and the companies whose logos are shown above.

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Preface

This is the first of a series of Study Reports prepared during research into base isolation of low rise buildings. Reference is made to four BRANZ unpublished preliminary reports on this subject. However, the key findings from these unpublished reports are reproduced herein.

Acknowledgements

This work was jointly funded by the Building Research Levy, the Foundation for Research, Science and Technology from the Public Good Science Fund, and the companies whose logos are shown on the cover page.

Note

This report is intended for researchers, structural engineers, manufacturers and other workers in the field of seismic resistance of low rise buildings.

BASE ISOLATION OF LOW RISE LIGHT AND MEDIUM-WEIGHT BUILDINGS

BRANZ Study Report SR 156 (2006)
SJ Thurston

REFERENCE

Thurston SJ. 2006. 'Base Isolation of Low Rise Light And Medium-Weight Buildings'. BRANZ *Study Report SR 156*. BRANZ Ltd, Judgeford, New Zealand.

ABSTRACT

The potential for application of the Roglider™ and Roball™ base-isolation systems for seismic protection of low rise building is examined. It was concluded that most buildings would be susceptible to excessive movement under wind loading, unless the isolators were placed under concrete floor slabs when the weight of the structure above (factored by the effective isolator friction coefficient) would often be adequate to resist the wind forces while still giving good seismic protection. A set-up using this arrangement was tested. The protection given to contents was examined and it was noted that protection for 'rocking body' type contents (e.g. bottles) was small.

A literature survey was performed to examine other types of isolation systems. A modification of two of these was selected as being the most likely candidates for general application.

KEYWORDS

Base isolation, residential, houses, slip layers, Roglider, low rise, seismic, earthquake, seismic isolation, low cost, seismic protection.

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1. INTRODUCTION

1.1 Purpose of this document

This document has been prepared to meet the BRANZ year 2004–2005 revised contract with GNS to meet Objective 2 (New Applications of Seismic Isolation) in PGSF contract number C05X0301 and part of the BRANZ year 2005–2007 revised contract with GNS. In the year 2006–2007 it is envisaged that further investigation and testing of the most promising base-isolation system(s) will be undertaken by BRANZ.

Other parties to this contract are GNS and Robinson Seismic Ltd. The response of isolated buildings and the effectiveness of isolation to protect building contents is been investigated by GNS using computer simulation. Robinson Seismic Ltd continues developing the Roball™ and Roglider™ base-isolation devices (BIDs).

1.2 BRANZ reports for this contract in the 2003–2004 years

BRANZ provided the following three reports which are briefly summarised below and described in greater detail in Section 2.

Report SR0920/1 showed that isolation systems will generally only be economically viable if the purpose is to protect building contents, as the cost of isolation cannot generally be justified by savings in the costs of structural elements or reduced structural damage. Isolation is expected to be mainly used in new structures, although it may have some application in retrofit situations.

The report also showed that excessive movements under the design wind loading are likely in most isolation of light-weight building scenarios if the proposed friction type isolators are placed under the timber floors. However, if the isolators are instead placed under concrete floors, and the wind zone is no greater than medium, design wind levels are not expected to induce any movement at the isolation level. This is because the lateral 'friction' force to initiate wind-induced movement increases greatly due to the added weight above the isolator. However in high wind design areas, wind-induced movement is still likely to preclude the simpler form of friction dampers from being used. Use of isolator systems with significant secondary slope may be a solution in these instances. The concrete floor located on top of the isolators is likely to be either a pre-cast floor system or else be cast using permanent formwork.

Report SR0920/2 was provided in response to the contract requirements to "Assist with the determination of performance specifications for base-isolation systems for light-weight structures, specifically by providing selected input parameters for computer modelling work to be carried out by GNS". BRANZ assumed that the building superstructure would remain essentially elastic (being protected by isolation). The report provided information regarding the building vertical mass and stiffness distribution and the building damping ratio. The light-weight structures were interpreted as being conventional building construction, less than 10 m in height, which complies with the scope of NZS 3604: 1999. Buildings with suspended concrete floors, concrete columns or concrete shear walls were not considered, as it is intended that these heavier structures are examined in subsequent stages of this objective.

Report SR0920/3 provided sketches of various construction details and summarised the design considerations for such construction. The systems were for installation of isolators under both timber and concrete floors, even though the former is unlikely to be viable except for buildings located in high seismic coupled with low wind zones, or where special provision is made for wind loading. The installation details are critically dependent on the expected seismic movement across the isolators. Separate analysis is being undertaken by GNS to determine the design movement based on appropriate earthquake records. Building services need to be specifically detailed to accommodate this movement – but this aspect was not covered in this report.

1.3 Buildings suitable for isolation

Reports SR0920/1 and SR0920/3 identified that the following five NZS 3604 building types (single or two storey) may be suitable for isolation in high earthquake, low wind risk areas, provided they have heavy roofs and at least medium-weight wall claddings. The fifth building type may also be suitable for medium wind zones and for average weight construction. Buildings outside this scope are likely to experience excessive movement under design level wind pressures.

(1). Buildings founded on anchor, braced or cantilever piles with isolation devices between pile top and bearer. The isolation devices may be the proposed Roball or Roglider systems or else simple proprietary systems such as the Lumberlok or Timberlink may perform some base-isolation role.

(2). Buildings founded on building perimeter continuous concrete walls with interior piles. The isolation devices are placed between the top of the walls and the house perimeter bearers/joists. Sliding devices are placed between interior piles and the bearers.

(3). Buildings founded on a timber floor constructed on top of isolation devices placed on either a concrete slab on grade or else a rigid concrete basement.

(4). Buildings founded on a timber floor constructed on top of isolation devices placed on concrete blocks with pairs of bearers used above.

(5). Buildings founded on a concrete floor (probably pre-cast) located on top of isolation devices placed on a concrete slab on grade, a concrete basement or concrete pads.

1.4 BRANZ scope of work for the 2004–2005 years

Based on the results of the first year's investigations, BRANZ's scope of work for the second year of the objective was modified to be "construction and testing of a base-isolated floor system". The purpose was to:

- derive suitable details to enable similar base-isolation systems to be constructed economically
- examine the constructability of using base isolation
- report on problems encountered, such as achieving level surfaces at each isolator location
- derive procedures and guidance notes on critical construction aspects and order of construction to ensure the final construction will perform adequately as a base-isolated structure
- test a full-scale construction to see if problems arise during seismic loading which could not be seen in simpler tests of single isolators
- check the relationship between loading speed and isolator effective friction coefficient
- check the performance of Roglider isolators, both with and without a 'skirt'. The skirt is the perimeter rubber panels designed to give a restoring force and a secondary stiffness
- move the isolated floors to the displacements expected from earthquake and simulated seismic loading to determine if deterioration of performance or damage to the isolators occurs.

- experimentally assess whether the tested base isolation gives seismic protection to building contents when subjected to the design earthquakes. (This phase of testing imposes floor movement as determined from the GNS computer simulations.) Record the slip and falling of the contents tested for the purpose of calibrating a ‘rocking body’ computer model.

The scope of work described above was achieved and the results were reported in BRANZ report SR0920/4. This is summarised in Section 2.4. At the end of the testing, the isolators were stored in a field environment with the intention of repeat testing after several years’ exposure to the elements.

1.5 BRANZ scope of work for the 2006–2007 years

The initial objective of the BRANZ input to this project was to develop practical construction details for installation of the Roball and Roglider BIDs into light-weight and medium-weight buildings. These devices were simultaneously being developed by Robinson Seismic Ltd.

After showing that the isolation devices under consideration for light-weight buildings needed to be under a concrete slab, or otherwise the building would be susceptible to wind movement, BRANZ designed and tested such a system with the results being reported in SR0920/4.

BRANZ subsequently advised GNS that the most promising system for installation of these devices for medium-weight buildings was the same system as for light-weight buildings. However, as these buildings could be given good seismic protection relatively inexpensively without base isolation, and the cost of base isolation using the best construction method conceived to date is high, the system was deemed to be non-viable. BRANZ then asked GNS for advice on how it should proceed.

Following discussions and meetings between GNS and BRANZ, the scope of the work was modified to be:

- perform a literature survey of cheap base-isolation systems suitable for base isolation of low rise light and medium-weight buildings
- summarise the results to date in a Study Report
- select the most promising system and undertake sufficient preliminary testing to enable its potential to be assessed.

This report achieves the objectives apart from the testing of the selected system.

2. DETAILED SUMMARY OF PREVIOUS BRANZ REPORTS

2.1 Report SR0920/1

2.1.1 House types which cannot be isolated using the Roglider or Roball base isolators due to potential wind movement

It is important that the BIDs do not move excessively under low wind loading as regular movement will disturb the house occupants. However, it is the potential movement under the ultimate limit state design wind forces which is more critical as discussed in the paragraph below.

If yielding of BIDs occurs under the design ‘3 second’ gust wind speed, the house may displace excessively unless ‘stops’ are provided. If the house hits ‘stops’, an impact force will be imparted to the house which may cause damage. The report therefore recommended that the design base-isolation yield force (BIYF) be greater than the ultimate limit state wind design force at the isolator level.

As a quick estimate of the likely movement (if the wind force exceeds the BIYF) consider a house of mass, M, and BIYF = 0.1 Mg subjected to a constant '3 second' gust wind force 10% higher than the BIYF (i.e. 0.11 Mg). The house will therefore accelerate at 0.01 g for 3 s which (using the well known formula s = ut + 0.5at2) will cause the house to displace a distance of 0.5 x 0.01 x 9.81 x 32 = 0.44 m. This is expected to be close to a practical upper limit of allowable movement.

The wind design force, FW, on isolators under a 'standardised' house can be found from Table 5.5 of NZS 3604 for each NZS 3604 building wind zone. The weight, W, of buildings for each of the 33 building classifications in the NZS 3604 earthquake loadings tables (roof and wall cladding weight divisions and roof pitch) was calculated. Assuming that the buildings would slip on the isolators at a friction coefficient of μ, the minimum friction value of μ to prevent sliding was calculated from:

μ = FW/(W/1.2).

The 1.2 factor was introduced, as the building weights are banded with only the maximum values being used in the calculations and W/1.2 was considered to be closer to the average weights. For instance, a heavy roof is defined in NZS 3604 as being between 20 and 60 kg/m2. The weight assumed in the calculation was 60/1.2 = 50 kg/m2.

The results are shown in Figure 1 and Figure 2 for the NZS 3604 high and low wind speeds zones, respectively. Also shown on the plot are Roglider and Roball slip coefficients. Clearly, only the very heavy buildings in low wind zones will not be susceptible to wind slippage using the criteria described above.

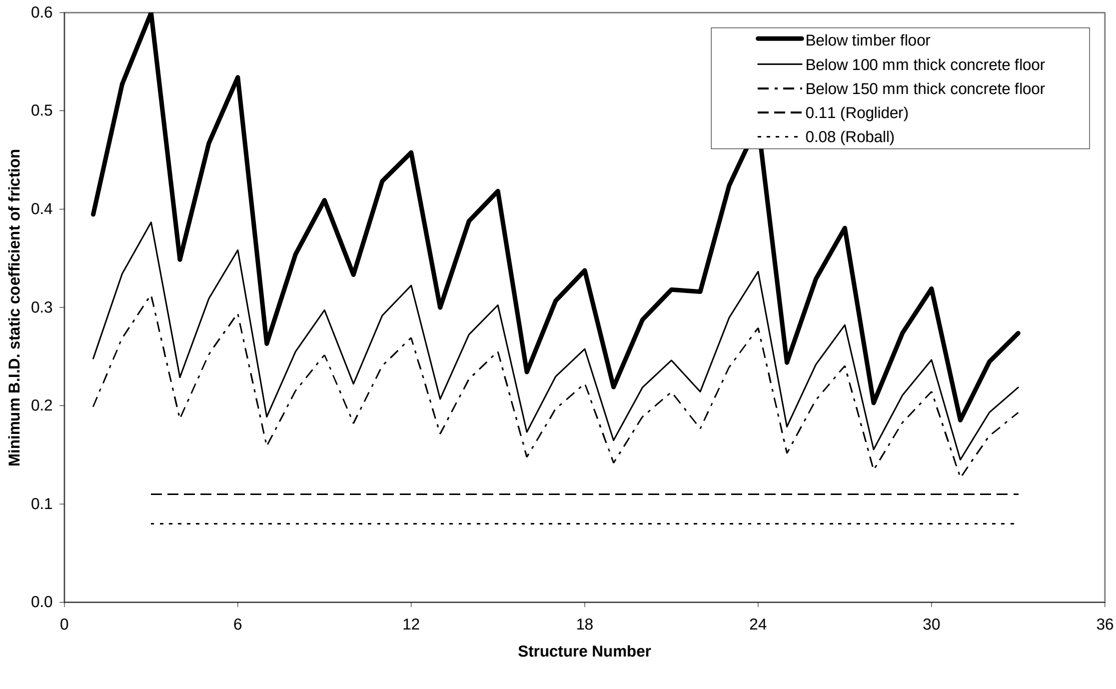


Figure 1. **Minimum coefficient, μ, for isolators under a two storey house from NZS 3604 for high winds.**

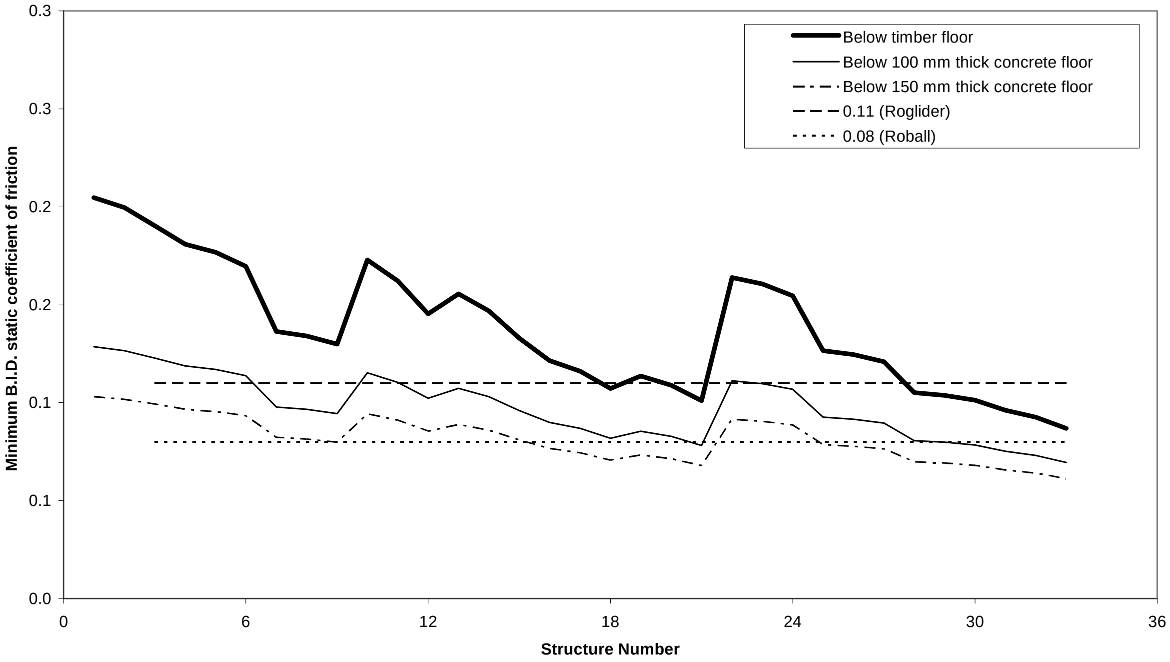


Figure 2. Minimum coefficient, μ, for isolators under a two storey house from NZS 3604 for low winds.

2.1.2 House types which cannot be isolated due to potential wind movement as a function of isolator friction coefficient

To examine the relationship between the percentage of buildings unsuitable for isolation and the base slip coefficient, a detailed analysis was performed using the BRANZ confidential database. This database lists details of construction used, and location within New Zealand, in a statistical sample of 2954 houses constructed in the last three years. It is interesting to note that 91% of these buildings were built on a concrete slab. Those founded on a concrete slab were assumed to have the isolators under a 100 mm thick concrete slab.

The results are shown in Figure 3. The plot for buildings constructed with isolators under a timber foundation is somewhat stepped, which is a reflection of the smaller number of houses considered (only 259) and also the stepwise nature of construction weights assumed. This plot shows that few houses with isolators under timber foundations will be suitable for isolation. The plot looks more ‘hopeful’ for buildings with isolators under concrete slabs. However, use of a concrete floor above the isolators is likely to require either a pre-cast concrete slab or else permanent formwork which are expensive options.

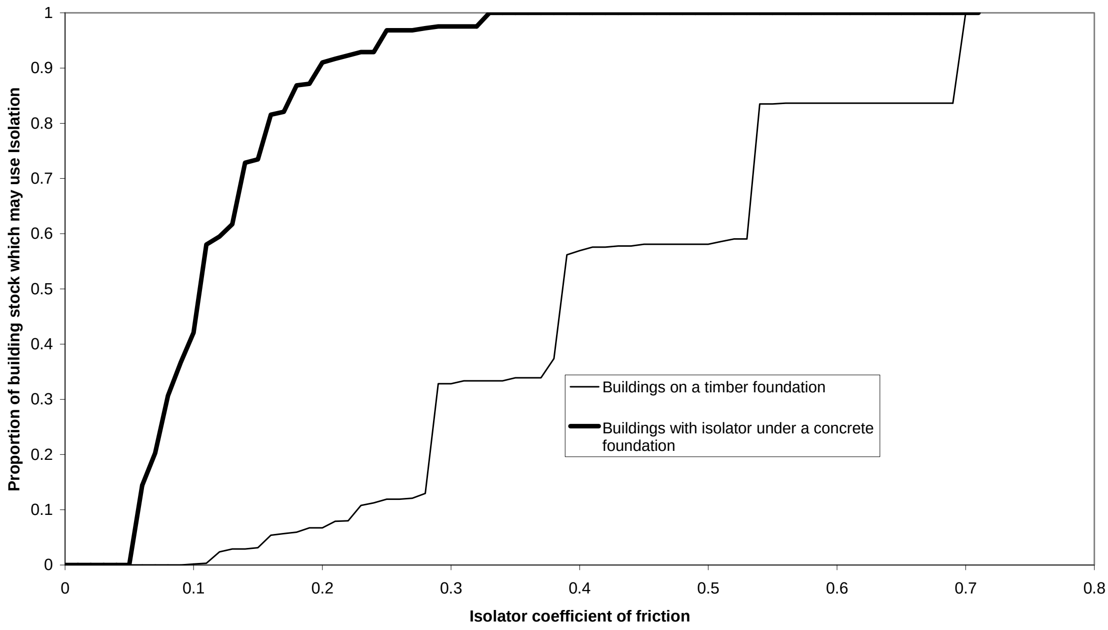


Figure 3. Plot showing ratio of buildings which may be isolated versus isolator coefficient of friction.

2.2 Report SR0920/2

For two building plan areas (10 m x 10 m and 20 m x 20 m), this report provided the background assumptions and values for building weights for NZS 3604 type buildings recommended for use in GNS computer time history analyses. Values were given for the 33 building weight arrangements considered in NZS 3604.

Data for building inter-storey stiffnesses, pile stiffnesses and damping were also given.

2.3 Report SR0920/3

This report provided sketches of various options for using the Roball or Roglider base-isolation systems in light-weight low rise structures. It also briefly discusses how standard commercially available connection systems between piles and house superstructure, and conventional braced piles in themselves, will provide a base-isolation role if a sufficient seismic load is imposed on the superstructure above. The possibility of providing yielding elements in a diagonal brace was discussed.

2.3.1 Principles of base isolation

Figure 4 is a pictorial representation of the action of isolation in an earthquake using a Roball, Roglider or elastomeric bearing BIDs. A stop may be used to limit excessive movements. The practicalities of construction, installing the devices, crawl spaces for inspection, maintenance and system durability must be considered.

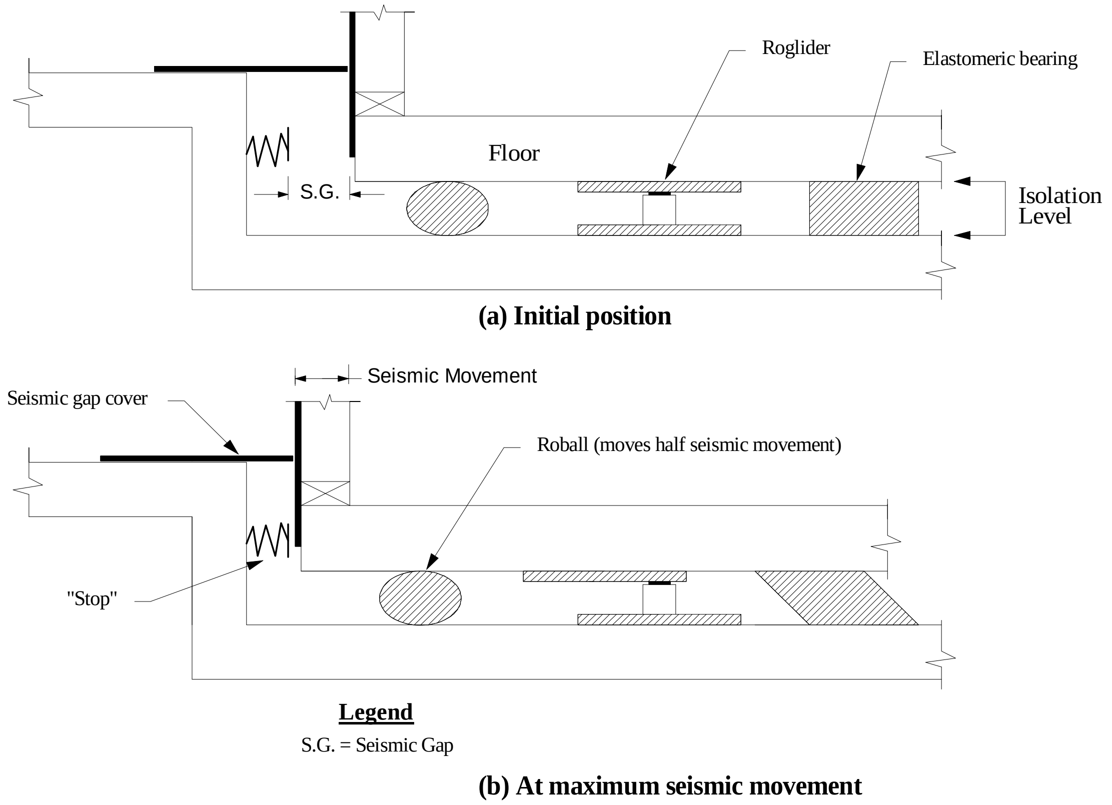


Figure 4. Schematic illustration of installation and operation of isolation devices.

A diaphragm is required above and below the BIDs as discussed in Section 4.2. The diaphragm below may be the ground itself or a concrete slab. The diaphragm above may be a timber floor or concrete slab. The practicalities of suspending the concrete floor means the floor must be pre-cast and craned into position, or else for cast in situ construction adequate clearance must be provided to place and remove formwork etc, otherwise the formwork must be permanent. to avoid 2 x 'or else' in this sentence These are all expensive options. Other considerations are:

- replacement/maintenance of isolators (if required) is a problem as access is difficult
- floor slabs need to be designed to span between BIDs
- achieving an effective diaphragm above the BIDs is difficult on sloping or multi-level sites
- slabs may need thickening along the edge
- paths etc need to be kept clear of the slab, which must have a seismic gap all round.

2.3.2 Mixed systems/sloping sites

Mixed systems may be used as shown in Figure 5, but the designer needs to appreciate that the seismic movement at each BID in the direction shown in the drawing is the same. Thus, all piles must have a lateral strength of at least the base isolator yield force which implies that:

- all piles will need to be braced in both directions or else be anchor or cantilever piles
- all piles need to have significant lateral resistance, and the 'ordinary' piles as defined in NZS 3604 may not be used as they are unlikely to have adequate lateral strength
- a BID needs to be provided at each pile
- the joist and bearer roll-over forces as stipulated in NZS 3604 must be resisted.

Alternatively the piles themselves may act as isolators – this may be achieved if the piles are designed to 'rock'.

The diaphragm above the isolators needs to move as a whole to avoid rupture, and thus needs to be continuous over the entire floor, or else requires a strong connection between the different parts as illustrated in Figure 5.

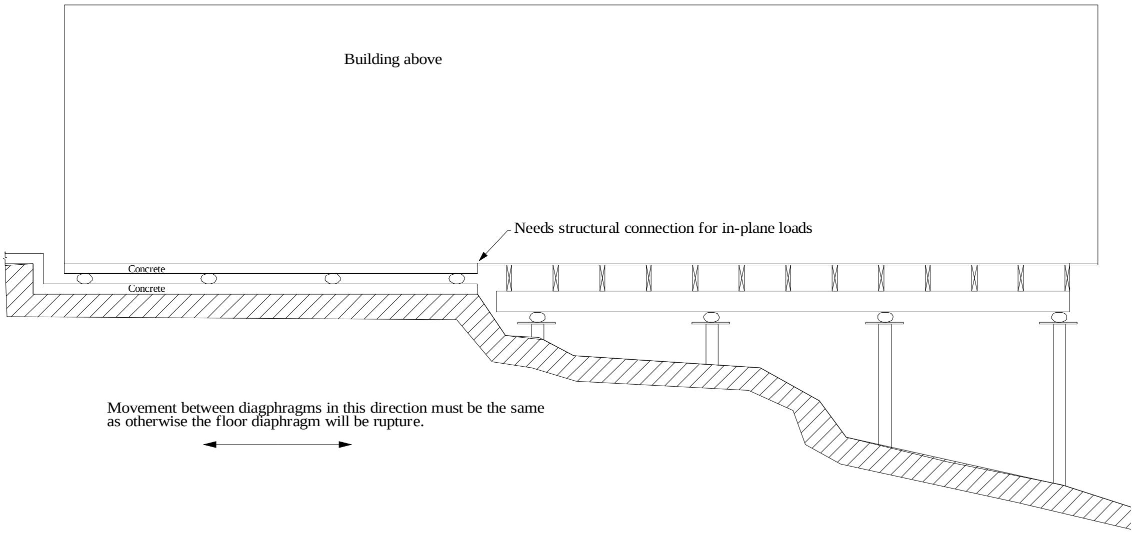


Figure 5. Figurative view of isolation of mixed concrete/timber floor systems.

2.3.3 Connection between pile top and joist/bearer

A proposed isolation system located between pile and bearer is illustrated in Figure 6 for each isolator type (Roball and Roglider). It will be noted that the joint must be able to sustain a bending moment of HxD1+VxD2 where H is the yield force of the BID and V is the vertical load transferred to the pile. It was concluded that the construction proposed would require careful design to be able to carry these moments and prevent pile failure, bearer twisting and instability and would most likely be unsuitable. However, this evolved into the more robust solution of Figure 8.

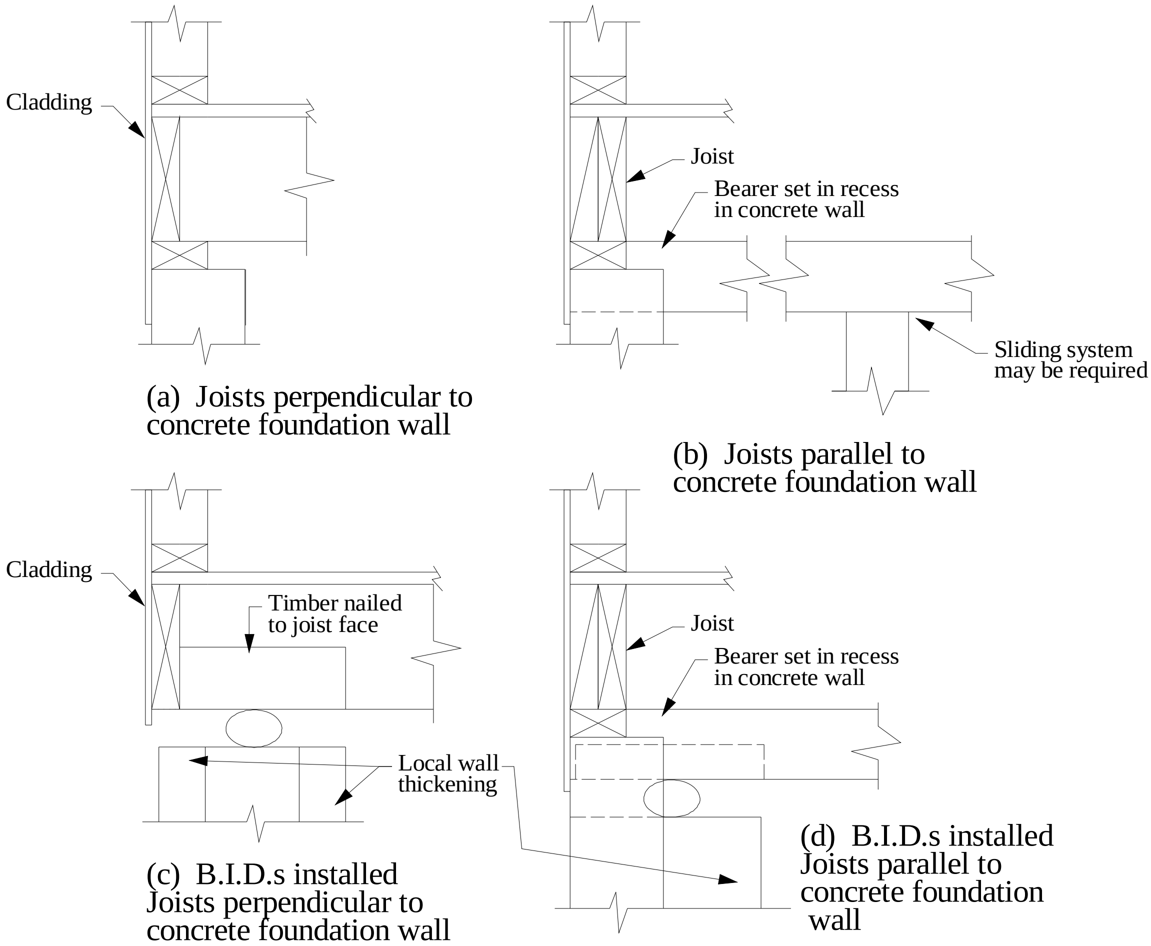


Figure 6. Isolation devices between piles and timber floors.

2.3.4 Connection between continuous foundation walls and joists/bearers

Figure 7 (a) and (b) show typical details for connecting conventional houses to continuous concrete foundation walls. Joists perpendicular to the foundation wall sit on timber plates which are bolted to the wall as shown in Figure 7 (a). Bearers perpendicular to the foundation walls sit in rebates in the wall as shown in Figure 7 (b).

Generally these systems rely on a strong floor diaphragm to transmit all the horizontal forces to the concrete foundation walls which are parallel to the direction of the seismic force. The internal piles for these systems are normally just simple ‘ordinary piles’ which are shallow and have little lateral load capability. If the bearers are connected directly to these piles the imposition of the diaphragm seismic movement is likely to ‘rock’ the pile. Alternatively, the rocking movement of the pile may result in the pile top rupturing the floor. A sliding device may be required at these piles to enable the floor to slide relative to the piles without transferring a large lateral load.

A possible system for using BIDs (either Roball or Roglider) at continuous concrete walls is shown for the two major directions in Figure 7 (c) and (d). These require local thickening of the concrete wall, which is assumed cannot extend past the wall plane, and also widening of the joist and bearer bearing surfaces as shown. These will only be practical options if the required seismic movement is not excessive.

The concrete exterior walls are strong in the in-plane direction, but are weak in the out-of-plane direction. Hence, in the proposed base-isolated systems of Figure 7(c) and (d), earthquakes perpendicular to foundation walls will still require large movement across the BIDs perpendicular to the walls and therefore the yield force of the BIDs must be transmitted perpendicular to the wall. Imposition of these forces is likely to rock the walls, which may cause some damage. For instance, if the diaphragm moves 150 mm on the isolators, then foundation walls perpendicular to this motion will move 150 mm in the out-of-plane direction which will cause damage, particularly at wall corners.

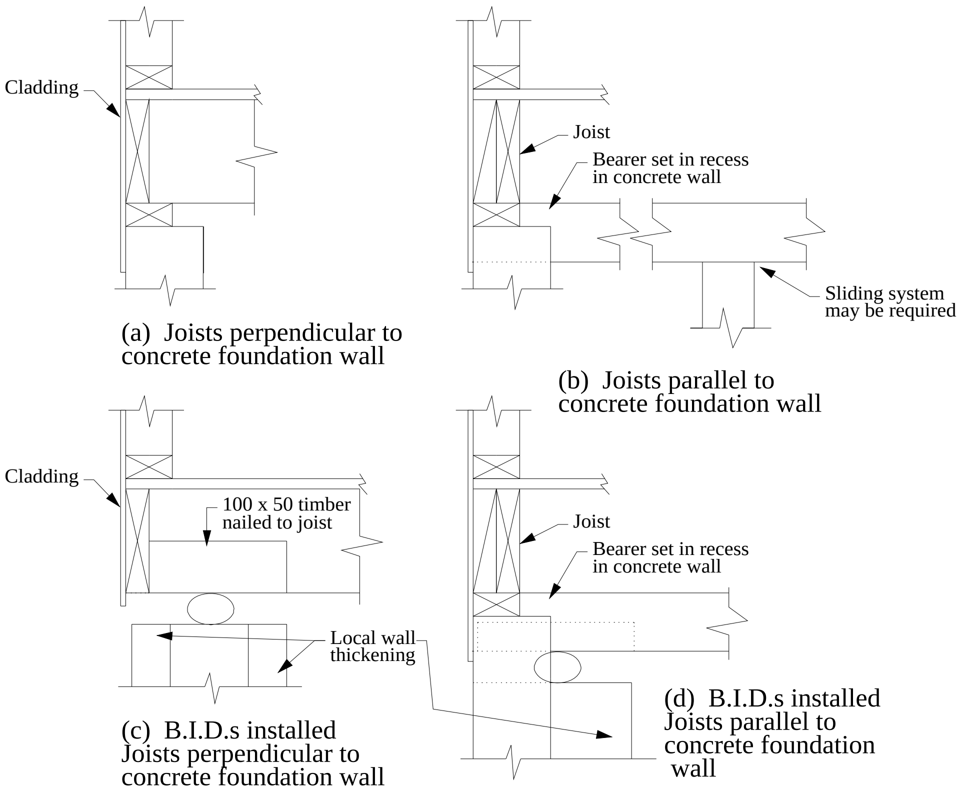


Figure 7. Perimeter isolation at houses with continuous concrete perimeter walls but piled in the interior space.

2.3.5 Base isolation for timber building using concrete foundation blocks and bearer pairs

Another option for buildings on timber floors is sketched in Figure 8. This is as per conventional construction, except that bearers are placed in pairs as shown.

The concrete blocks are cast in situ to precisely the correct level in a shallow hole (minimum value from NZS 3604 is 200 mm deep) dug into the ground. A plaster surface topping on the top surface of the block or packing may alternatively be used to take up tolerances.

Section 6.14.4 of NZS 3604 requires a minimum gap of 450 mm beneath floor joist as a crawl space. Assuming that the combined height of the Roball plus bearer is 160 mm high, the top of the concrete block must be a minimum of 290 mm above the ground level. Assuming that the block is embedded 200 mm into the ground results in a minimum block depth of, say, 500 mm. A block depth of 500 mm has been sketched below.

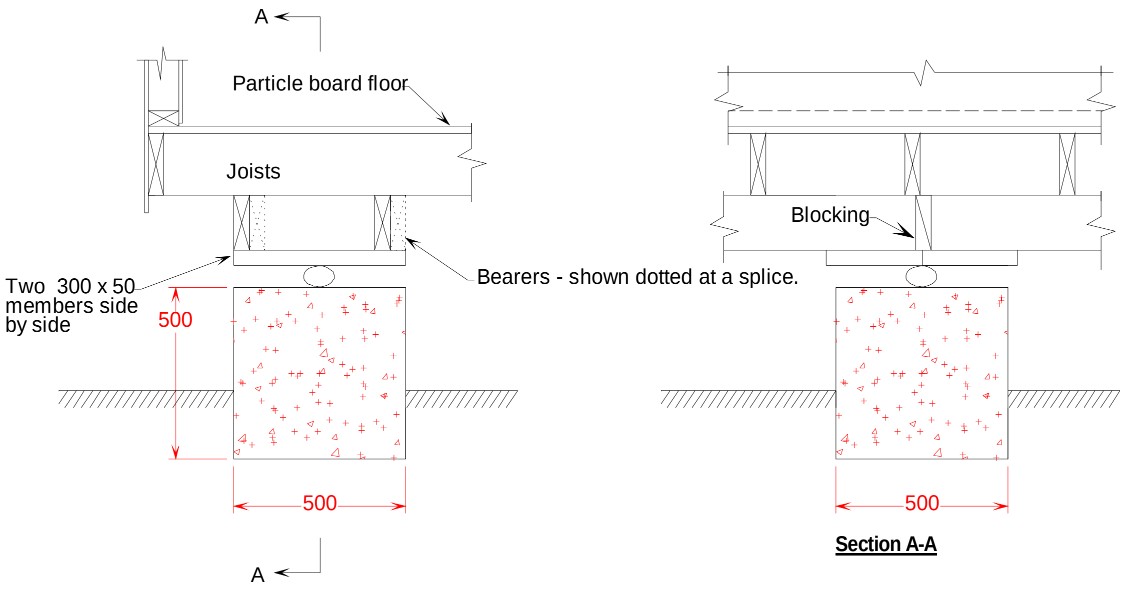


Figure 8. Base-isolation system using bearer pairs and base blocks.

2.4 Report SR0920/4

BRANZ constructed and tested a Roglider base-isolation system to examine the practicality of the system. Detailed comments were made on difficult aspects of construction (e.g. how to achieve a levelled floor) and methods used to achieve the end result were discussed to provide guidance for others undertaking similar work. A brief discussion of the construction, testing and interpretation follows, but greater detail is given in the original report.

2.4.1 Description of the base-isolated building being simulated in the BRANZ tests

Figure 9 and Figure 10 shows the construction of the base-isolation system as proposed for use in actual buildings which was simulated in the BRANZ tests. The floor consists of Stresscrete Unispan slabs which are 1.2 or 2.4 m wide and span half or the full width of the building as shown in Figure 2. Concrete topping is used on top of the pre-cast slabs and a conventional house constructed on this base. Pre-cast concrete beams, placed on top of the isolators, support the ends of the Stresscrete Unispan floor slabs (see Figure 9 and Figure 10).

The foundation is formed by digging holes of sufficient depth to give adequate bearing in the ground. These are filled with concrete at each planned isolator position. (Where isolators are close it may be more economical to make this a trench.) Pre-cast concrete blocks are then cast on this foundation at each isolator position. The spacing of the blocks depends on the spanning capacity of the pre-cast support beams. The isolators are bolted to the tops of the blocks and also to the bottom of the pre-cast support beams (see Figure 10) .

2.4.2 Construction tested in Report SR0920/4

The test construction consisted only of the floor slab and substructure as shown in Figure 11. The superstructure in a real structure will be built on the floor slab. As the superstructure is designed to remain elastic, and thus effectively rigid during the shaking, it was considered that it may be simulated purely by adding mass to the top of the floor slab. This mass would increase the load on the isolators and thus have an influence on their final size. However, as the isolators were designed for the actual test axial load to be placed upon them, in terms of the purpose of the study, there was no point in adding this mass.

Four pre-cast concrete blocks were placed on the laboratory concrete floor at the appropriate positions. They were not fixed to the floor, as the maximum lateral load that the Rogliders were expected to be able to transmit was less than the force which would cause block sliding or rocking. The Rogliders, pre-cast concrete beams and the pre-cast concrete slab were then positioned as shown in Figure 11 and the concrete topping added.

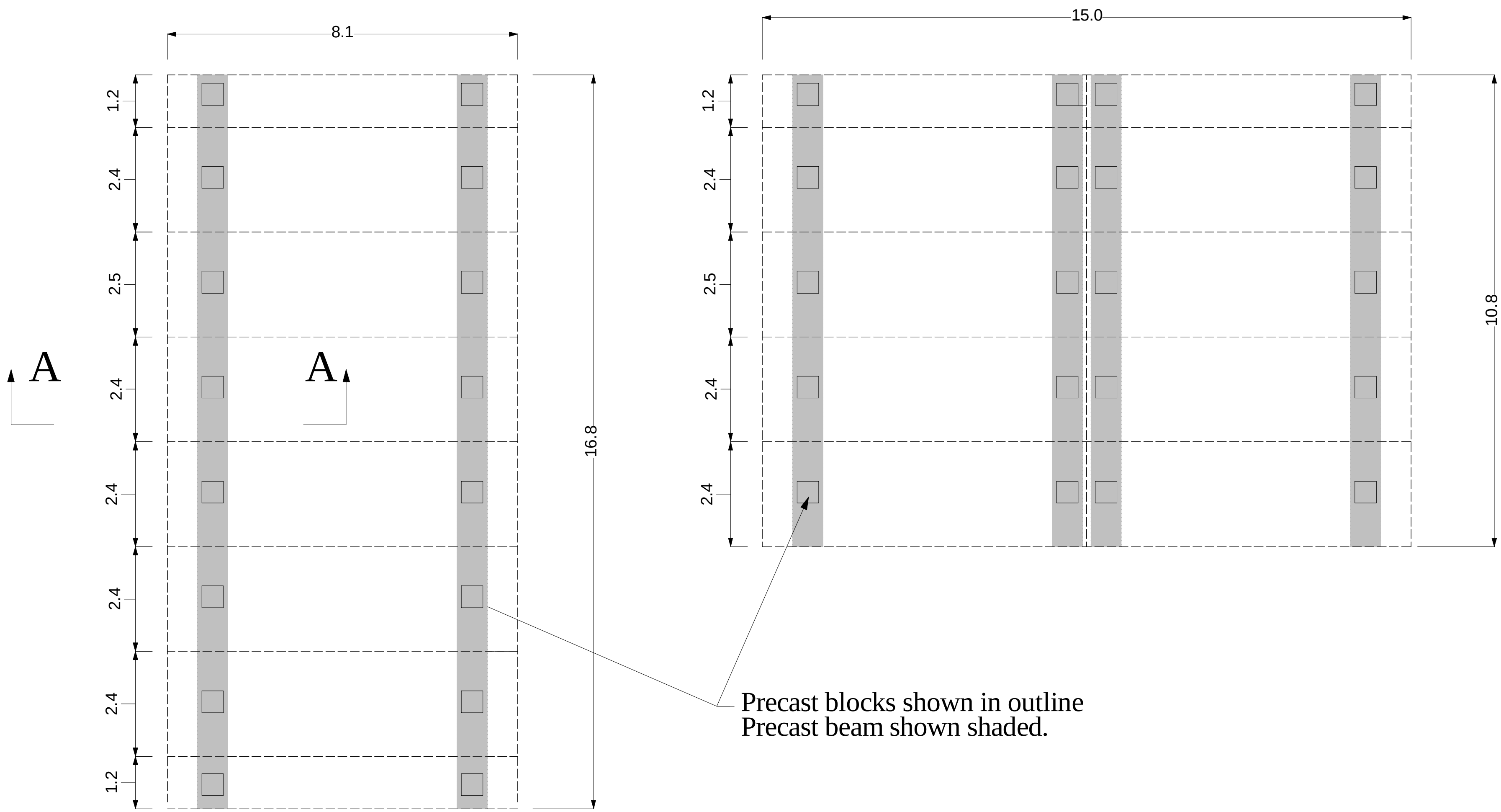


Figure 9. Plan showing possible concrete block and Unislab layout.

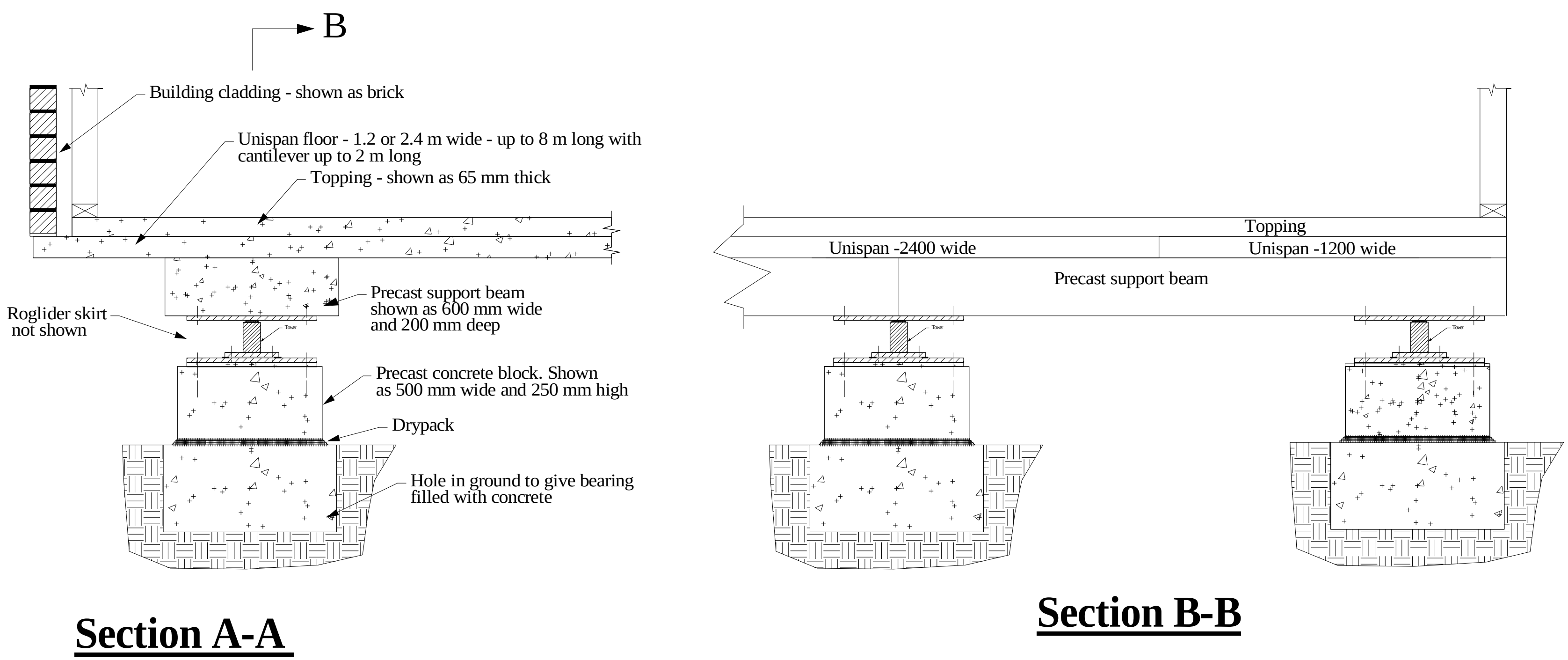


Figure 10. Cross-section views of proposed typical houses.

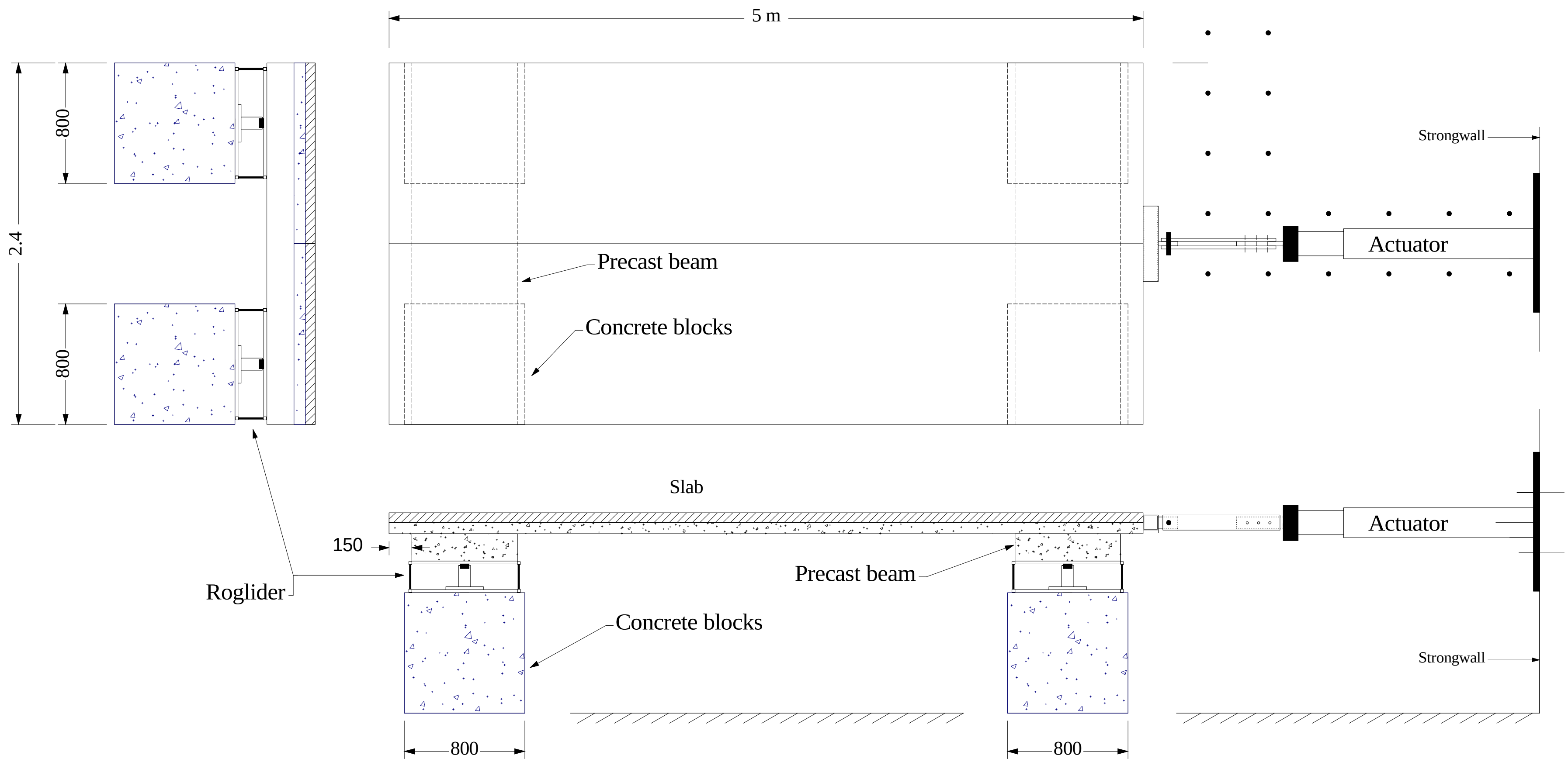


Figure 11. General view of test construction.

2.4.3 General description of testing set-up

Figure 12 shows the general test arrangement used. An actuator shown on the LHS of this photograph displaced the base-isolated floor. Figure 13 shows the supports at large imposed displacements. The tower (see Figure 13) can be considered a fulcrum below the pre-cast beam with the moments resulting from the following actions about the fulcrum being in balance:

(1) The vertical reaction on the tower due to the weight of the top slab.
(2) The vertical reaction on the tower due to the weight of the pre-cast beam.
(3) The horizontal reaction on the tower from the applied actuator force which is transmitted across the isolator.

If the vertical loads are insufficient to balance the horizontal load, then the arrangement will become a mechanism (i.e. unstable) and the pre-cast beam will rotate around the fulcrum. This is most likely to occur at large displacements or if the horizontal load becomes large.

Figure 14 shows bottles placed in preparation for the 'rocking body' tests. Figure 15 shows the residue from wear on the Teflon pads from the various tests described below. However, as the total movement at this stage was approximately 65 m, this amount of wear is not surprising. Figure 16 shows the deformation of the rubber panels (skirts) during the sinusoidal displacement of the floor to ±70 mm. At 120 mm displacement the system became unstable (for reasons explained in the paragraph above). Figure 17 shows this situation at 140 mm push displacement. For the purposes of taking this photograph the outside rubber panel was removed.

Figure 12. General photograph of test set-up.

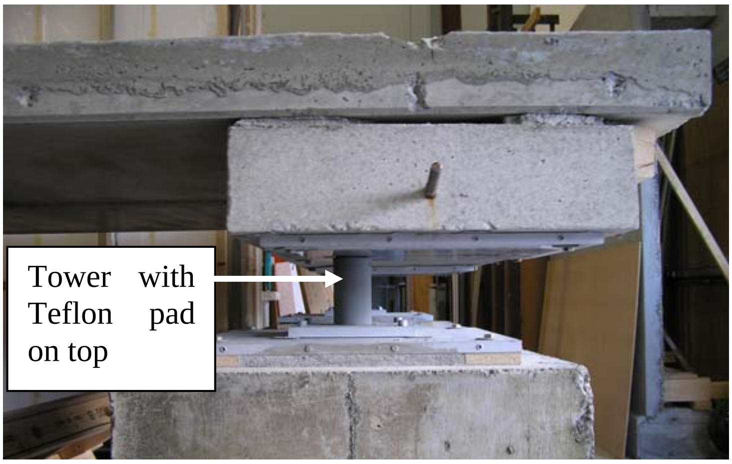


Figure 13. Push 160 mm movement.

Figure 14. Bottles placed for 'rocking body' tests.

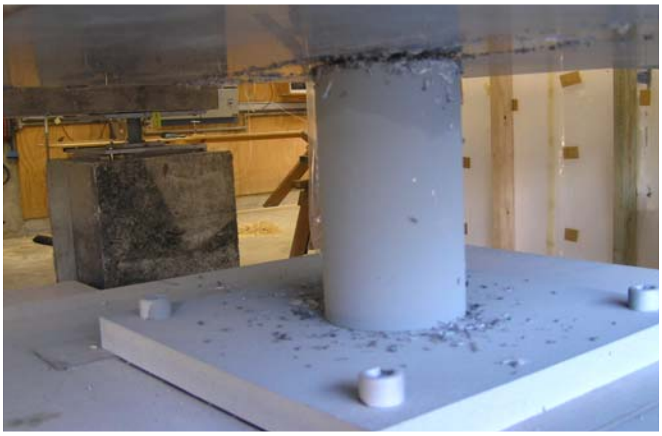


Figure 15. Wear on the Teflon pads.

Figure 16. Push 70 mm with 'skirts' on.

Figure 17. Static displacement to 140 mm with front 'skirt' removed.

2.4.4 Sinusoidal motion

(a) Rubber 'skirt' not in place

Sinusoidal motion was applied at selected displacements and frequencies and the applied force and floor movement measured.

Figure 18 shows the hysteresis loops generated from a slow sinusoidal motion to a displacement, D, of 80 mm. The hysteresis loops are close to rectangular, with lower forces near the end of the strokes (when the velocity was lowest) and a spike at the change in direction.

Figure 19 shows the same plot but at a frequency, f, of 0.5 Hz. The maximum speed in this test can be found by simple harmonic motion theory as = $2\pi fD = 2\pi \times 0.5 \times 80 = 251$ mm/s, which is approximately half the expected design earthquake demand velocity. Figure 19 shows significant oscillation of load and is significantly different from the rectangular shape of Figure 18. Note that the force plotted includes the inertia force to drive the mass of the slab etc. The theoretical inertial force was subtracted to give the best estimate of the force transmitted across the isolator. This correction was W/g x (2πf)2 x D where W = measured weight of moved masses and g = acceleration due to gravity. The resulting plot, Figure 20, still shows the oscillations, but is now of more rectangular shape. Note that the force is significantly greater than that measured in Figure 18 which implies increase in isolator friction forces with increased puck velocity (i.e. velocity of the puck of Teflon relative to the steel plate).

The ratio of the corrected force when the harmonic motion displacement passed through zero to the total weight on the isolators was calculated for many sinusoidal excitation runs. The first set was measured early in the test series. The loading apparatus was subsequently modified to remove some minor 'slop' and the process eventually repeated. The results are plotted in Figure 21. The coefficient of friction so obtained was slightly higher in the BRANZ tests than measured by Robinson Seismic Ltd, particularly at higher displacements and in the second series of tests.

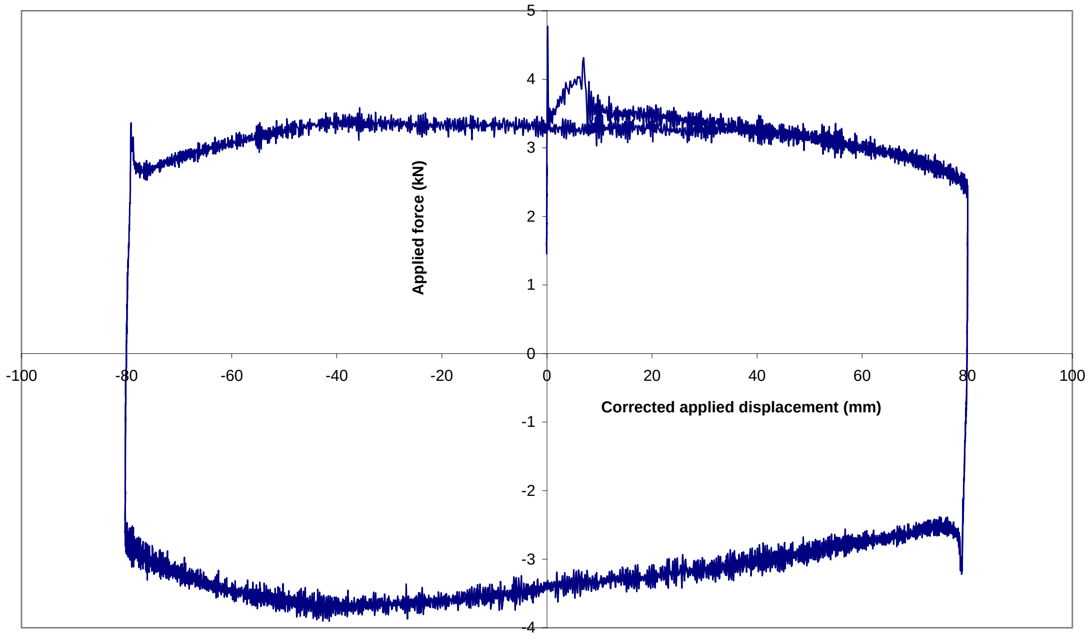


Figure 18. Hysteresis loops for sinusoidal floor displacement to 80 mm at 0.01 Hz.

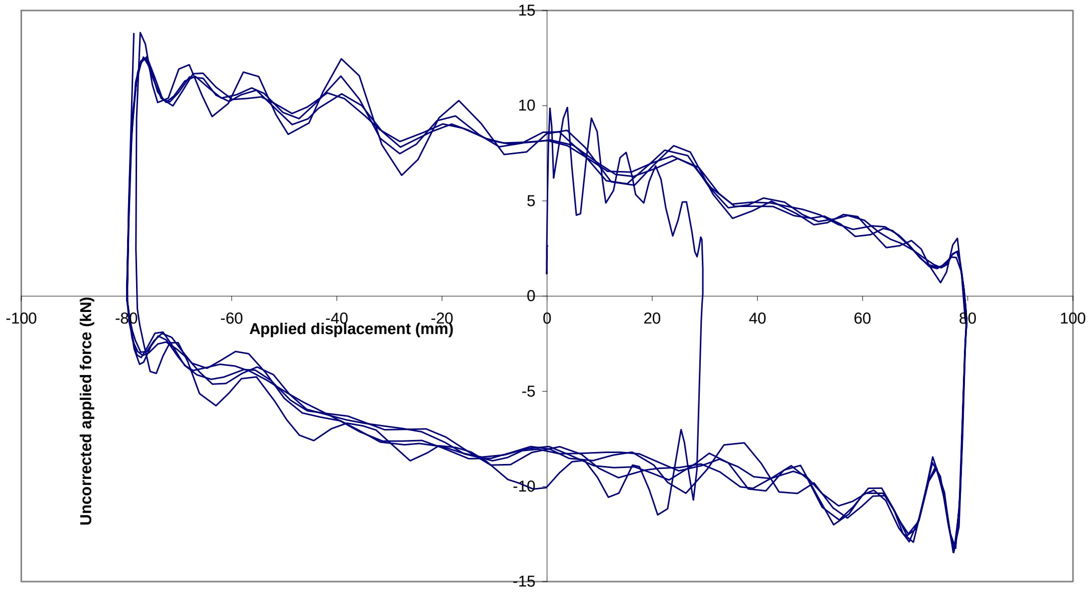


Figure 19. Uncorrected hysteresis loops for sinusoidal displacement to 80 mm at 0.5 Hz.

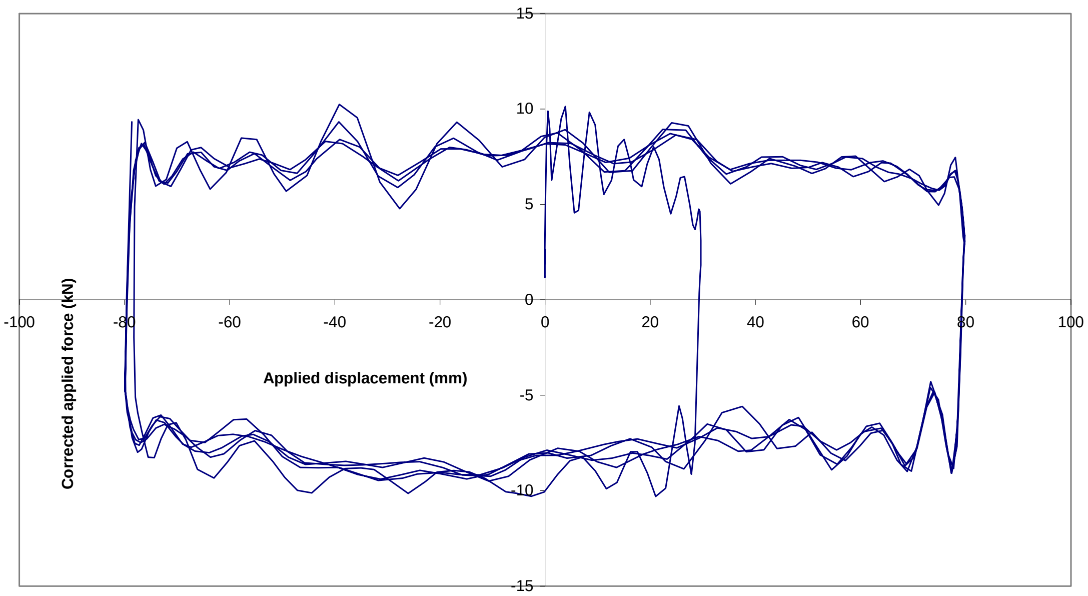


Figure 20. Corrected hysteresis loops for sinusoidal displacement to 80 mm at 0.5 Hz.

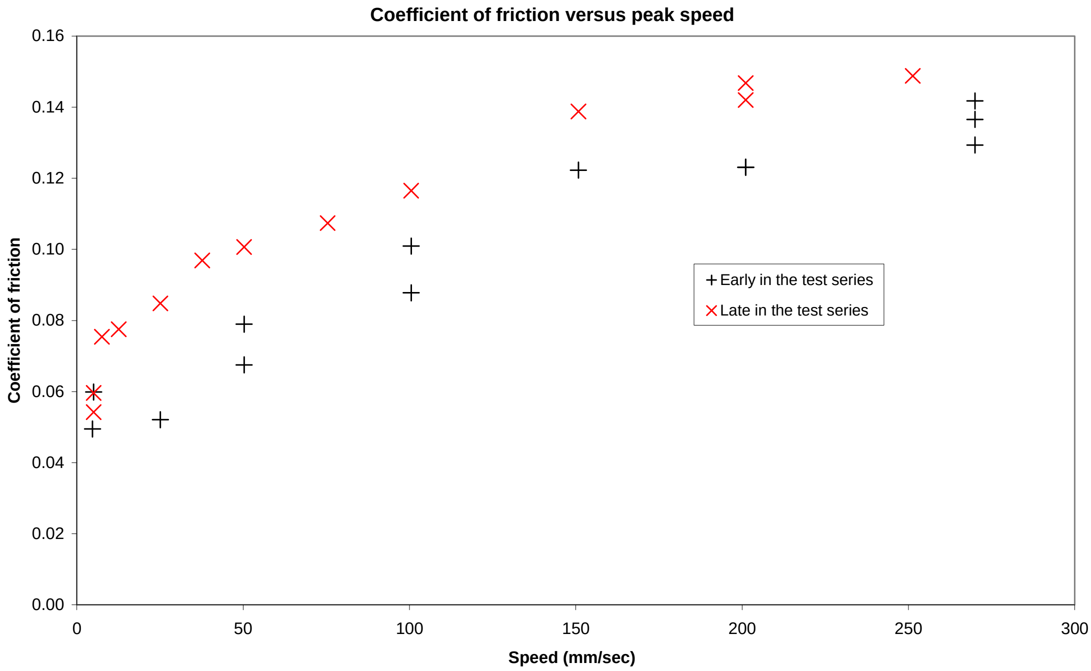


Figure 21. Effective isolator coefficient of friction at zero displacement.

(b) Rubber 'skirt' in place

The stiffness of the rubber skirt was far greater than expected. This resulted in a greater force being transmitted and the system becoming unstable at high displacements (see Figure 17). Care will need to be taken in actual building design to ensure that this does not happen.

Over 30 cycles to displacements peaking somewhere in the range 80 and 160 mm were imposed. At all times the rubber panels performed well and did not show any deterioration.

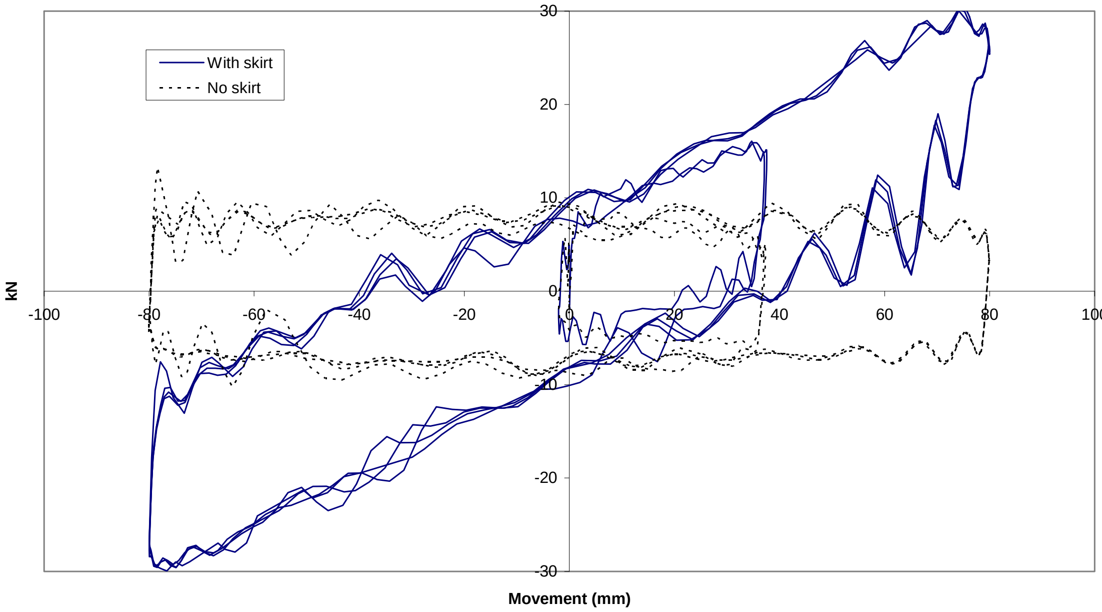


Figure 22. Comparison of hysteresis loops (with and without 'skirt'). Corrected force versus displacement (0.4 Hz, +/-80 mm).

2.4.5 Stability of Roglider isolator system as tested

The base isolator system as tested is shown in Figure 23(b), except that the slab is shown separated vertically from the beam for clarity.

Without the skirts on, the slab moved freely backwards and forwards above the isolator for the design distance of ±160 mm without significant beam rotation as shown in Figure 13. However, with the skirts the force across the isolator increased dramatically and at large displacements the beams rocked as shown in Figure 17. Figure 23(c) shows the forces on the beam. Rocking will occur when the moment caused by the forces F(earthquake) +W(beam) exceed the correcting moment from W(slab).

A preferred arrangement is to invert the isolator as shown in Figure 23(a). The force W(beam) then always acts through the isolator. Rocking can still occur when the moment caused by the force F(earthquake) exceeds the correcting moment from W(slab) i.e:

F(earthquake) x H >W(slab) x (beam width/2) ……. (1)

However, for typical geometry this implies an isolator coefficient of friction ≈1, which is unrealistic. Thus, the system is far more stable and is recommended to be used.

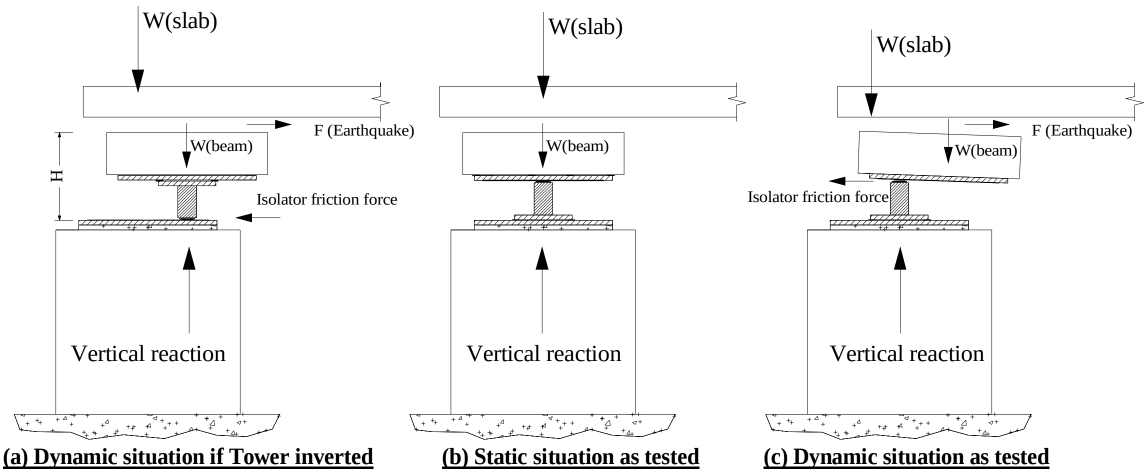


Figure 23. Forces on concrete beam.

2.4.6 Simulated earthquake motion

GNS analysed the seismic response of a mass fixed to a Roglider.[1] The N-S and E-W components of three earthquakes records, each including a 'near fault factor', were simulated for each of three Roglider models (called Cases). This resulted in 2 x 3 x 3 = 18 time history floor motions. BRANZ moved the test floor to these motions to:

(a) show that the Rogliders could withstand such differential movement
(b) measure the response of 'rocking bodies' to these motions to help calibrate the GNS computer model.

The simulated earthquake motion runs were performed without the rubber panels (skirts). At all times the isolator system performed well.

2.4.7 Dominance of wind loading

Base isolation may make a light structure vulnerable to excessive motion across the isolated layer under extreme winds. Placement of the isolators under a heavy floor slab will help to rectify this. The report included an analysis of a base-isolated building to examine its susceptibility to wind movement. The results indicated the proposed base-isolation system using Rogliders could be used for buildings in a medium wind zone, but not in a high wind zone.

2.4.8 Protection of building contents

Base isolation of light-weight structures is likely to be only economically viable when it provides protection to valuable contents. These contents are likely to include many objects which will respond to earthquake motion by rocking or sliding.

Bottles were used as typical objects which would respond to shaking by 'rocking body' motion. The measurements and observations of the movement of the bottles during the imposed floor excitation is intended to be used to calibrate a 'rocking body' analysis computer package, which will be used to ascertain if the isolation system proposed will in fact provide protection for stored objects. The measured floor motions and target motions are available from BRANZ on request.

A subjective assessment was that many bottles fell and most moved significantly in the simulated earthquake motions. This would suggest that a useful degree of base isolation was not achieved. This conclusion is compatible with the comparison of acceleration response spectra from the raw ground motion and from floor motions predicted in a base-isolated structure. These data were generated by Zhang1 and are plotted by the author of this report in Figure 24. These show that there is negligible protection for single degree of freedom (SDOF) systems with a fundamental period greater than 0.5 s (which would include many 'rocking' contents).

2.4.9 Conclusions from Report SR0920/4

A proposed base-isolated floor was constructed and tested to ascertain potential problems in application of the method. The record of construction of floor reported herein resulted in some recommendations on the sequence and method for construction on-site to ensure the final structure would perform as a predictable isolated structure. The recommended procedures were intended to result in the most economical method of construction.

The testing showed that the isolators would undergo many earthquake excitations without excessive wear. The system tested remained stable up to motions of ±200 mm if no rubber panels (skirts) were used. The skirts used were excessively stiff and thus attracted high seismic forces. The outcome would be little protection to the building or contents. Further, the high shear forces induced resulted in the system becoming unstable at movements greater than ±120 mm. This is one aspect which needs to be checked in each specific design. By inverting the Roglider this report shows that a far more stable arrangement is obtained (see Section 2.4.5).

Design earthquake floor motions predicted for a design 475 year event in Wellington (including near fault effects) were imposed on the floor and the isolators performed well. Approximately 65 m of floor motion was imposed and the Teflon pucks on the isolators appeared to retain more than 50% of their protruding thickness.

The prevailing opinion is that base isolation will protect building contents – both due to the increased effective damping and to the period shift of the motion – with a low natural period being assumed for the contents. However, the contents of interest in the low rise light-weight buildings of this study tend to be of the 'rocking body' type which may have an effective period close to that of the isolated floor. The preliminary results of this report indicate that little protection is likely for such building contents and, in fact, they may be more susceptible in isolated buildings than in conventional buildings in an earthquake.

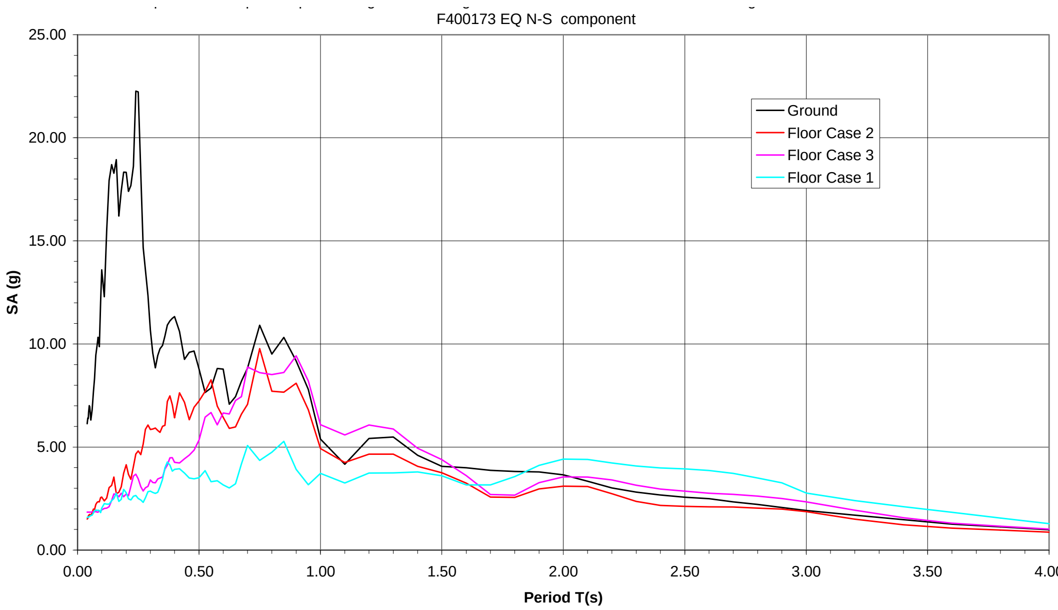


Figure 24. Comparison of acceleration spectra of raw earthquake signal and base-isolated floor.

3. GENERAL DISCUSSION ON ISOLATORS

Conventional seismic isolation can be expensive to implement and maintain and therefore only important structures have been so protected. For low rise buildings for which lateral resistance can be easily provided, the major justification for base isolation is protection of contents.

Many of the roller bearing base-isolation systems discussed have friction dampers with effectively a very low coefficient of friction (μ <1%). These need to be incorporated with lateral viscous dampers (piston type hydraulic arrangements) or lead rubber bearings to provide the buildings with adequate stiffness to resist wind loads and to avoid excessive earthquake deflection. Often this requirement is omitted from base-isolation research reports. A restoring force is also desirable to help centre the building after the earthquake, and this is often provided by a rubber bearing or by 'slope' methods, such as containing a roller within a cone.

An enormous amount of research funding has been spent over the past 10 years on attempting to develop and implement active control techniques for the seismic protection of buildings, and several buildings using active control systems have been built in Japan. There have also been proposals to develop smart isolators and intelligent isolation systems. The value of this research endeavour is questionable. It is unlikely to prove practical even for large, expensive structures and hence is not considered to be viable in the low rise buildings considered in this report.

Two types of base-isolation systems are the best known. The first is an elastomeric rubber-steel plate bearing system. The bearings are stiff in the vertical direction and flexible in the horizontal one, so the structure is isolated from the horizontal component of the ground motion. Energy absorption is usually achieved through use of lead cores or high damping rubber. The second type of base-isolation system includes rollers, sliding bearings or friction pendulums. To obtain a proper sliding motion, a low friction material (such as reinforced Teflon) is used in the sliding areas. Sliding base-isolation systems produce the isolation effect by limiting the force transferred to the structure through the isolation interface and by absorbing earthquake energy.

4. REQUIREMENTS AND PROBLEMS OF BASE ISOLATION

4.1 Requirements if isolators are used beneath masonry walls

Many researchers have proposed using base isolators beneath masonry walls. None of the literature surveyed has considered the large flexural demand this places on walls in the out-of-plane direction. An approximate analysis of the adequacy of such design is given below, which implies that this base-isolation method is unlikely to be viable. Appendix B contains a summary of typical construction of masonry houses in New Zealand.

Many proposals for use of isolators under masonry walls allow for little movement in the out-of-plane direction, which limits their effectiveness as isolators. P-Δ effects (Figure 27) need to be considered. Figure 27 indicates that the system can become unstable at large movements.

A 'stop' can be added to prevent extreme movements. However even if buffers are used, the impact forces can be large and could damage both the masonry walls and superstructure.

4.1.1 Seismic-induced forces on base-isolated masonry walls

To be effective in reducing forces on the superstructure, a base-isolation system must displace a significant distance during an earthquake. This is usually in the range ±100 to ±300 mm.

Consider the simple example of Figure 25. The building is supported on four exterior walls – A, B, C and D. If floor twist is ignored, all points on the floor above must move the same distance

– say 200 mm. It is assumed that the lateral stiffnesses of the base isolators are the same in both the X and Y direction. Thus the total force on each wall to impose the 200 mm deflection in the X direction is the same for all walls – say Fw.

(Note: it would be unwise to rely on walls which are perpendicular to the earthquake direction taking up this movement by ‘rocking’ action. Such deformation would induce significant damage, particularly at wall corners.)

4.1.2 Calculation of required wall strength

Consider a two storey house, 12 m x 12 m, with a 0.6 kPa roof, 0.7 kPa suspended floor (includes live load and partitions), and a 200 mm thick masonry wall on the exterior with 30% of the area being openings. This was taken to be a average weight of 14 kN/m.

Roof weight	=	12 x 12 x 0.6	=	86 kN
Floors and partition	=	12 x 12 x 0.7	=	100 kN
Wall self-weight	=	2 x (12 + 12) x 14	=	672 kN
		Total	=	**868 kN**

Assume the building is isolated at a level of 0.2 x building weight. Hence the force Fw = 0.2 x 868/4 = 43.4 kN.

From Figure 25(c) the maximum wall out-of-plane bending moment is approximately 43.4 x 2.4 = 104 kN m. This is resisted by a 12 m length of wall. Assume half the length is openings and the wall is reinforced by D12 bars at 400 centres. Thus, the wall strength is approximately:

M_{wall} = 0.9 x 113 x 0.3 x 0.9 x 0.1 x 12/2 = 16.5 kNm
Note M_{wall} is significantly less than the demand load of 104 kNm as calculated above.

4.1.3 Use of Rogliders beneath masonry walls

Figure 26 shows a proposal for use of Rogliders beneath masonry walls. If the coefficient of friction = 0.1, then slippage will occur when the horizontal load = 0.1P where P is the axial load per Roglider. Movements (slippage) of say 200 mm may be expected at the right hand side of two Rogliders. However, the stiffness/strength of the wall on the left hand side is unlikely to be adequate to transmit this load to the Roglider and thus the wall will ‘rock’. However, should it slide, which is the preferred mechanism, P-D effects are significant unless the isolator is attached to the top plate as shown in Figure 26(b), and the bottom plate is supported on a large flat concrete surface.

4.1.4 Conclusions

If base isolators are used under two storey masonry walls, the walls need to be designed for a large out-of-plane bending moment which will require special design. The connection between walls and roof needs to be strong.

For single storey buildings without continuity at the roof level, the walls are expected to ‘rock’ during earthquakes which will result in significant damage, particularly at corners.

Hence, although Appendix A provides several examples of use of isolators under masonry walls, both in research testing and structures that have been built, it is believed there is limited scope for this application and there are doubts about the likely performance where it has been applied.

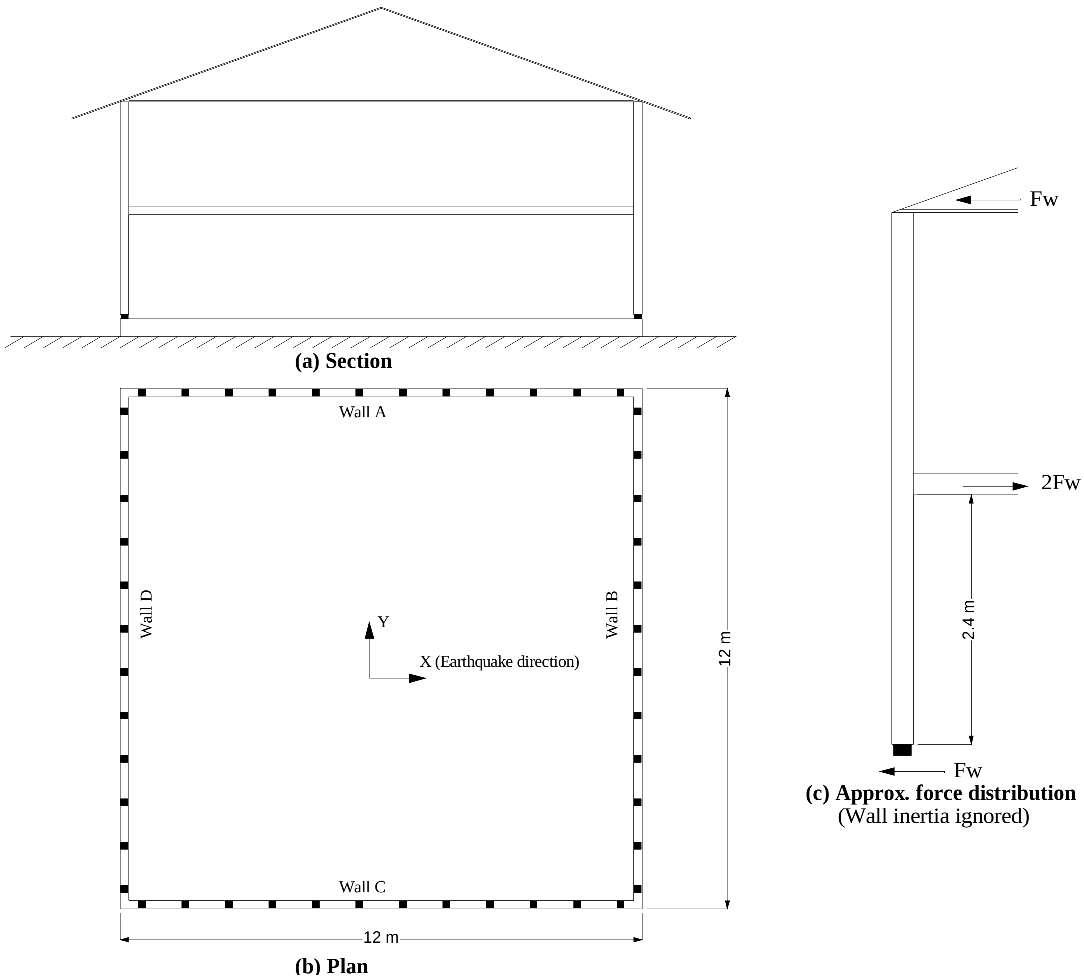


Figure 25. Out-of-plane forces on a base-isolated masonry wall.

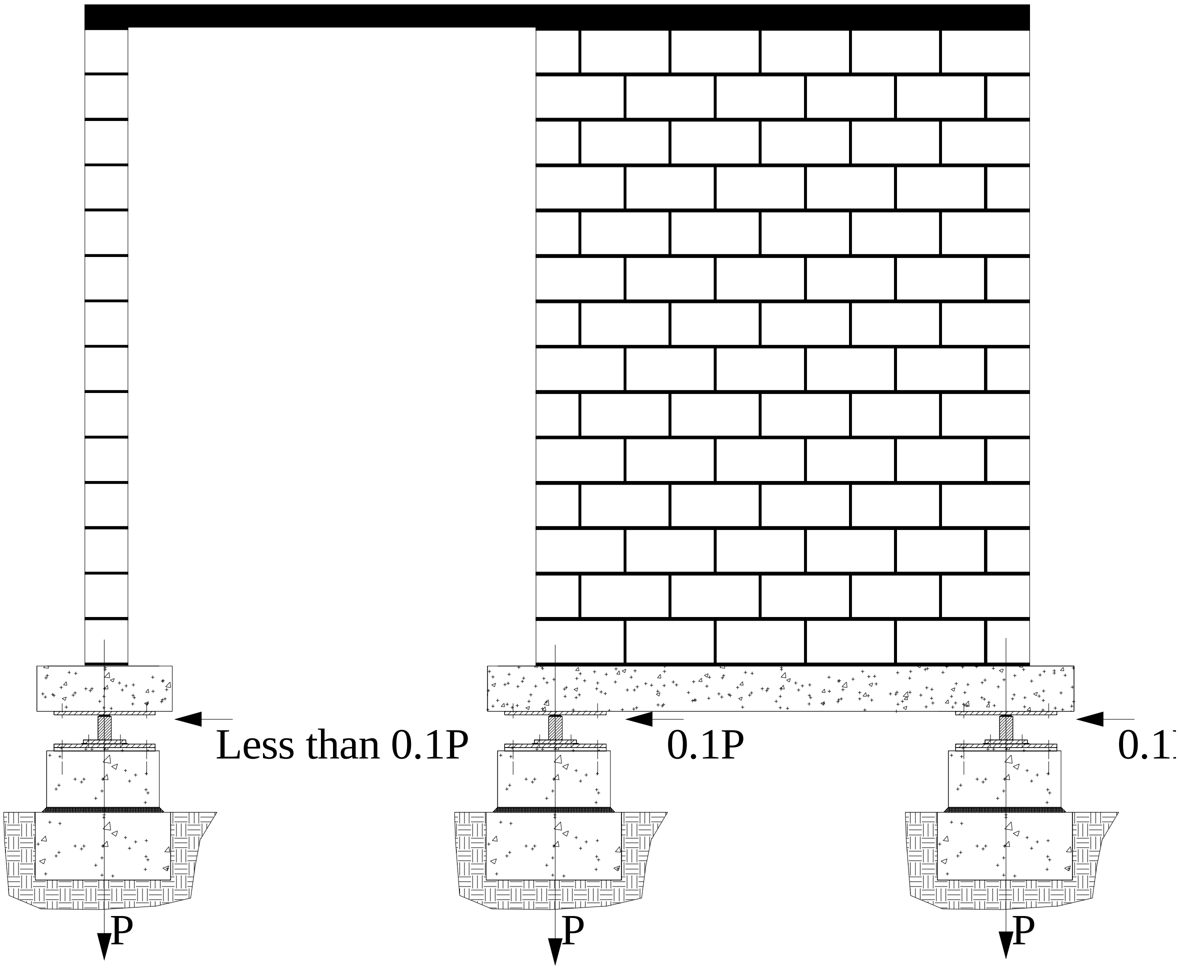
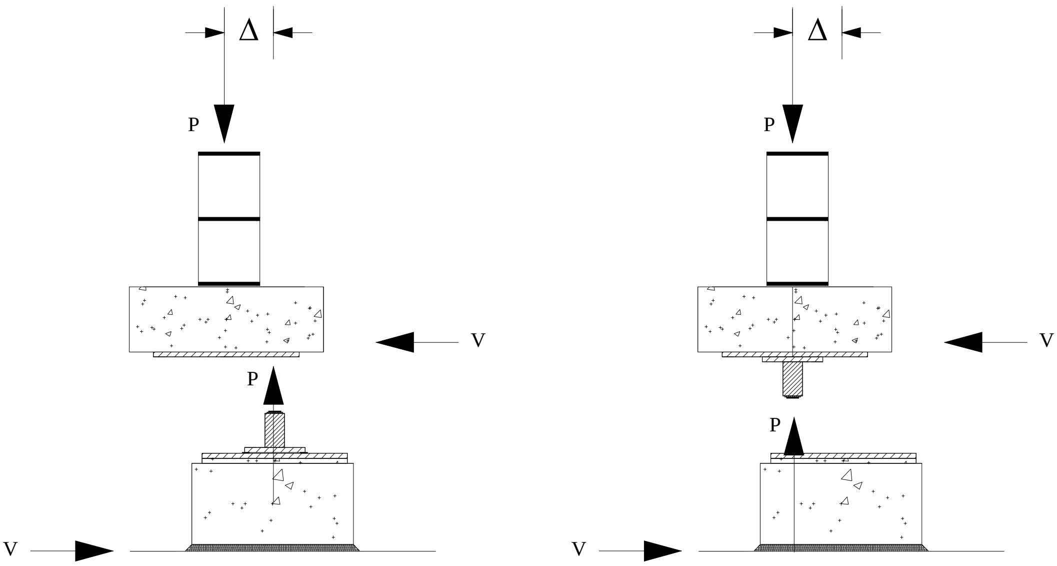


Figure 26. Use of Rogliders under masonry walls.



(a) Isolator attached to bottom plate **(a) Isolator inverted and attached to top plat**

Figure 27. P-Δ effects.

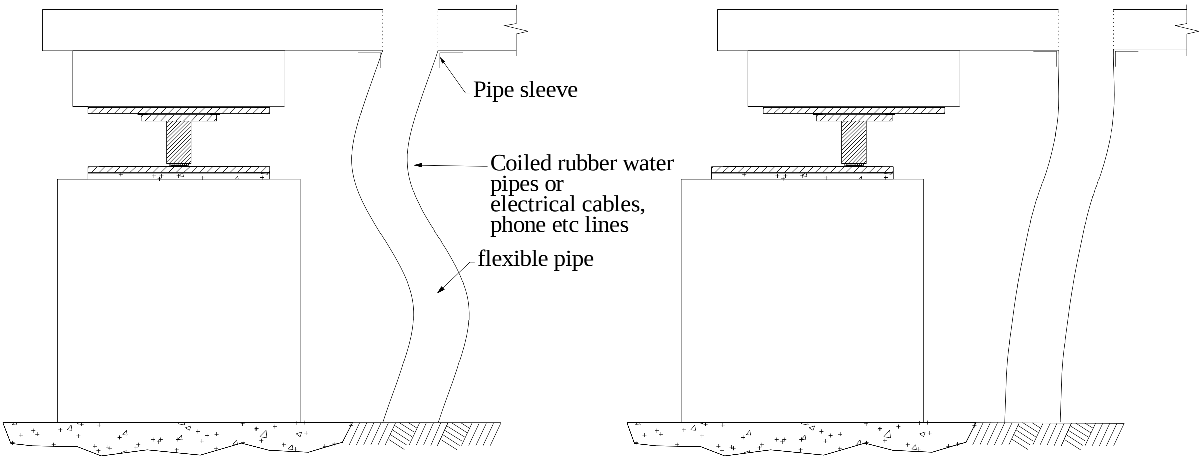


Figure 28. Coiling of services to ensure there is sufficient flexibility to deform to the required movement without rupture of services.

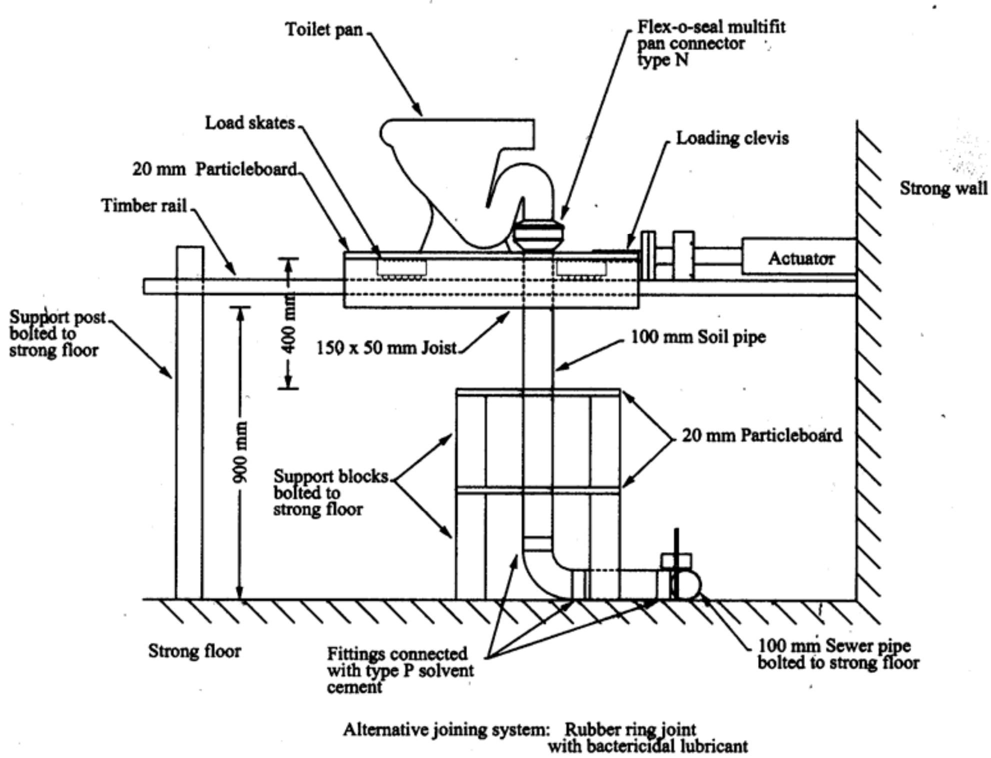


Figure 29. Test of a sewerage system at BRANZ.

4.2 Requirement for a diaphragm above and below a base isolator

The floor above the isolators must remain monolithic. The forces in the floor from the isolators below the floor are a function of the floor displacement, whereas the forces in the floor from the bracing elements above the floor are a function of the structural stiffness and masses of the structure above. These floors must act like a diaphragm to balance these forces.

Similarly, there must be a diaphragm below the isolators (this may be the ground).

4.2.1 Building services

Building services (electric cabling, water, sewerage), must cross the isolation storey to provide services to the building. It is important that these services remain undamaged after an earthquake event. Although typical design movements are large, e.g. ±200 mm, there have been many base-isolated buildings constructed and solutions are well known. The general method is to run the water and sewerage through flexible pipes (and place the electrical cabling within flexible pipes), and to coil these pipes to provide sufficient slack to take up the required movement without rupturing the services. This is illustrated in Figure 28. Tests at BRANZ (Figure 29) on a PVC sewerage pipe with flexible rubber gasket joints proved that large movements (±150 mm) would occur without rupture. Greater deflections were not investigated in these tests.

5. LITERATURE SURVEY UNDERTAKEN ON CHEAP ISOLATION SCHEMES

Appendix A is a literature survey of cheap and innovative base-isolation schemes for low rise buildings. The schemes proposed in each referenced paper are described and, where applicable, comments made on their deficiencies and potential for use in New Zealand.

Demonstration base-isolation buildings have been built in several countries, but mainly used lead-rubber bearings. As this is a known science, and the costs of this isolation scheme are relatively large, use of these isolators is not recommended for further study in this project. The construction used in these buildings would also be suitable for the Roglider, which this report has shown is unlikely to be viable in New Zealand.

The systems which appear to have most potential are those that have a slip layer beneath the building foundations, as the cost of this isolation system may be low. These are described in Section A2. Section 6 describes two systems based on Section A2 literature survey, but modified extensively at BRANZ to cater for typical New Zealand building construction and to solve various practical problems inherent within the published proposals. These two modified systems are submitted as being worthy of further investigation.

6. CHEAP AND SIMPLE ISOLATION SCHEMES WORTH INVESTIGATING

From the above work it was concluded that two base-isolation schemes were worthy of further investigation. These satisfy the following basic criteria:

1. The systems are simple and relatively cheap and easy to install.
2. They are located below sufficient mass so that wind effects will, in general, not govern.
3. The slip coefficients are low (in the range 0.06–0.2) and so will provide good seismic protection.
4. The system will not lead to water ingress problems from the foundation and, in fact, will provide resistance to water ingress.
5. There is little risk of the system causing instability.
6. Durability issues and lifetime reliability are expected to be satisfactory
7. Failure of the system will not worsen the building response from non-isolated building response. This is an important issue for acceptability to users.
8. The system can sustain multiple events without damage.

9. The system can be used with otherwise conventional construction for most house and low rise buildings used in New Zealand, including timber-framed buildings with light-weight exterior cladding, brick veneer and concrete and masonry wall construction.
10. Exterior footings can be made deeper to meet bearing pressure requirements from gravity loads from exterior walls.

However, on the negative side:

1. No consideration has currently been made to allow for movement to prevent damage to building services, such as water and sewerage reticulation and power and communication cables.
2. Clearance needs to be maintained around the building to allow the design seismic movement to occur without impedance or damage.
3. Steps, decking etc adjacent to the building will need to slide when pushed by the building during an earthquake.
4. The building is expected to be left with an offset displacement at the end of the earthquake and will need to be pushed back into position (possibly with a bulldozer).

6.1 System 1

Two variations of System 1 are shown in Figure 30. The first shows a brick veneer house wall system and the second a fibre-cement clad timber-framed wall system. However, the superstructures are interchangeable with the foundations and the two variations are shown purely to illustrate the small differences in foundations. Both variations can use synthetic liners, weak soils or pebbles as slip layers as proposed in references [2] to [7] in Appendix A. However, it is only the use of synthetic liners which will be discussed herein as this is the most promising method. The synthetic liner slip layers extend across the entire foundation and also act as a damp-proof course.

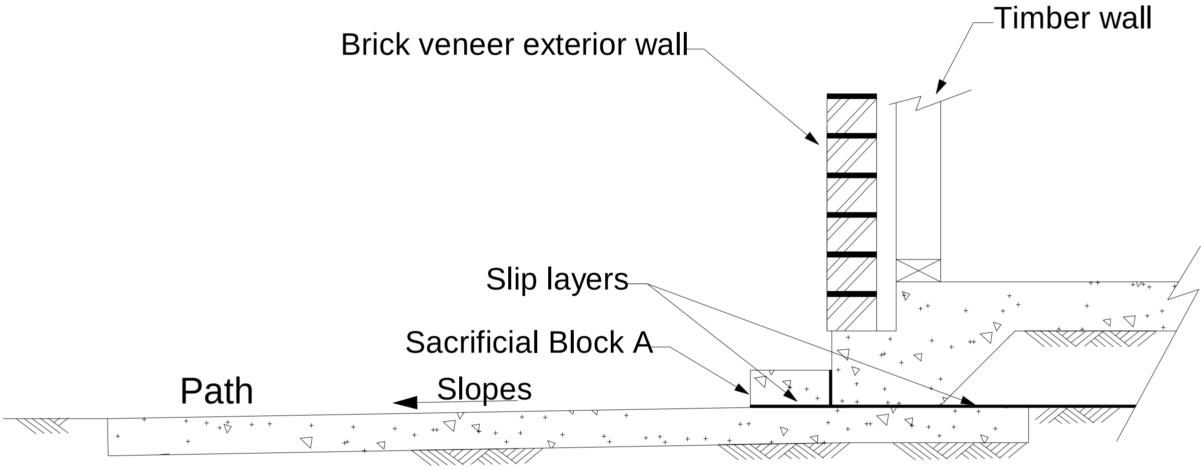
For variation (a) the path is first placed. The ground surface for the synthetic liner is then prepared and compacted smooth and the synthetic liner then placed. The hardfill between concrete and liner is then shaped and compacted and the concrete foundation poured.

A small sacrificial concrete slab is then poured adjacent to the exterior wall as shown. This is expected to be dislodged in an earthquake and its purpose is to protect the synthetic liner directly below from day-to-day wear. This slab will be of a width equal to the design seismic movement of the foundation. It can be pushed back into position after the event.

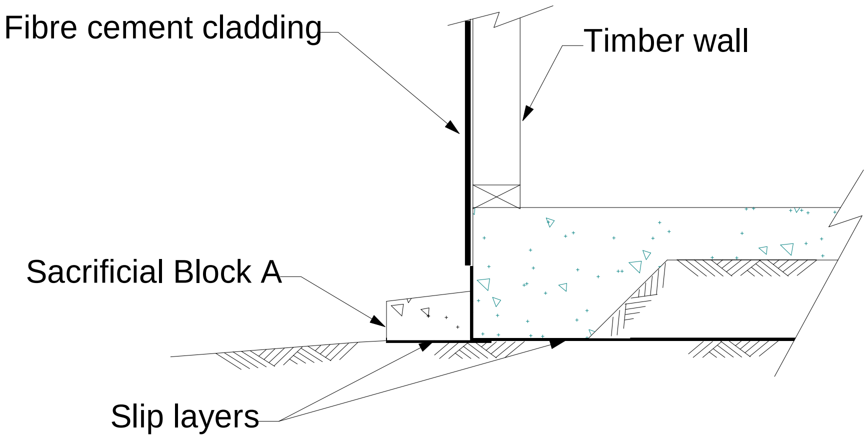
The synthetic liner may be wrapped around the main footing and a separate piece used below the sacrificial slab as shown in Figure 30(b) or, alternatively, it may pass beneath the sacrificial slab. In this instance, the slab must be separately sealed to the main footing. Figure 30(a) incorporates a concrete path on the house exterior, sloped at 1° away from the building, which provides extra bearing area for the exterior walls. This could be thickened underneath the walls if still greater bearing strength is required. Similarly, if needed, a loadbearing footing could be located under the exterior walls in Figure 30(b).

6.2 System 2

System 2 (Figure 31) is a variation, albeit a significant one, of the system described in reference [6] which was shown to work effectively in shake table tests. A hole is first dug into level ground to remove soil of low bearing capacity. A synthetic liner is placed across the whole foundations, but curved at the ends as shown. Backfill is then placed and compacted to form the substrate for the concrete foundations. The concrete is then placed. A path may optionally also be cast and, if so, it may need sitting on a synthetic liner also. This acts like the sacrificial slab of System 1. The whole foundation above the liner is intended to 'slosh' in a large earthquake, which relieves the vibration transmitted to the building.



(a) Conventional brick veneer house founded on concrete slab with slip layer below



(b) Conventional fibre-cement clad timber-framed house founded on concrete slab with slip layer below

Figure 30. System 1 – proposed for further investigation as the most promising base-isolation system.

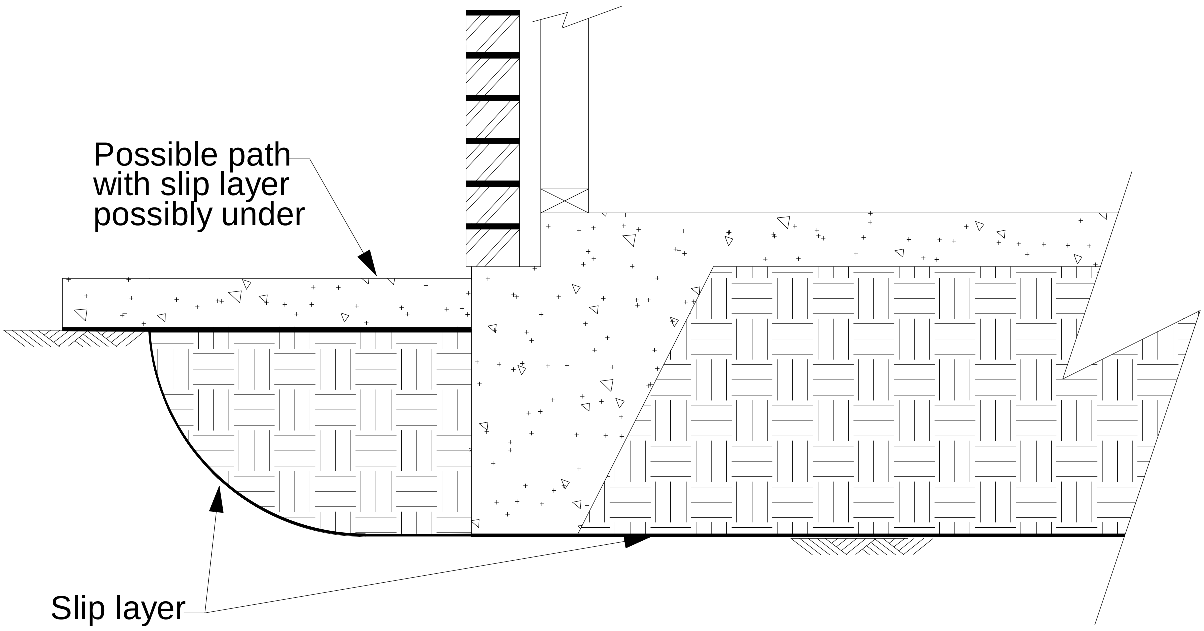


Figure 31. System 2 – proposed for further investigation as the second most promising base-isolation system.

7. CONCLUSION

This report has shown that the potential use of Roglider and Roball base isolation of New Zealand houses and other low rise buildings is low due to the following reasons:

- If the lateral load resistance of the isolation level is set sufficiently low that there is a significant reduction of design level seismic force in the superstructure, then most buildings will move excessively under design level wind forces, depending on the seismic and wind zones and building weights. This movement may be limited by use of stops, buffers or isolators with significant secondary stiffness, although this may reduce the seismic protection achieved.

  Placement of the isolators under ground level concrete floors or use of the isolators in medium-weight (e.g. masonry) buildings can, in some instances, avoid the problem but comes at an economic cost.

- Generally, providing additional lateral resistance to low rise structures is not a difficult or expensive exercise. Therefore, the relatively high cost of providing the isolation cannot be justified purely on the basis of savings in building structure. Note that life risk from collapse of the structure can be made to be low at the design stage without recourse to base isolation.

- The cost may be justified in particular structures where the value of the building contents is high or continued operation after an earthquake is imperative. However, the study indicates that protection of building contents with natural periods of 1–3 s will be low. This would cover most 'rocking bodies', such as bottles in a medical centre or cabinets, fridges, TVs etc. It is recommended that further study be made of the vulnerability of these items in base-isolated buildings.

- The cost of allowing for large seismic movement in the design of building services (water, sewerage, electrical, communications) can be significant.

To try and identify cheap effective isolation systems that could be used in New Zealand low rise buildings, a literature survey was performed. Many of the systems proposed were impractical, expensive, or their effectiveness and safety was dubious. However, two systems were identified as worthy of further investigation as described in Section 6. These show significant promise. It is recommended that this research projected, as defined in Section 1, be refocused on these systems.

8. REFERENCES

1. Zhang J. 2005. *Seismic Modelling and Testing of Base-Isolated House. Selection of Parameters for Rogliders, Generation of Floor Response Time-Histories.* Internal report by GNS.

9. ACKNOWLEDGEMENTS

BRANZ wishes to thank Stresscrete in Otaki for their kind donation of the floor slabs for the testing described in Section 2.4.

APPENDIX A. LITERATURE SURVEY OF BASE ISOLATION FOR LOW RISE LIGHT AND MEDIUM-WEIGHT BUILDINGS.

This Appendix gives the results of a literature survey of published research and application of innovative and inexpensive base-isolation schemes. For each paper of significance, it gives the reference, a summary of the paper contents and (where applicable) an interpretation of the paper and comments on its significance.

A.1 General discussion on isolators

[1] M Iiba, H Yamanouchi, M Midorikawa, S Yamaguchi, Y Ohashi and M Takayama. 1998. 'Research on Performance of Base Isolated House'. *Proceedings of the Second World Conference on Structural Control (Vol 2).*

The report authors proposed that the construction of a normal Japanese house be modified as shown in Figure 32 to accommodate a base isolator. This effectively consists of isolators sitting on a raised pedestal on the foundation. The house above is supported on a timber floor, which is itself supported on a grid of steel beams. It is considered that this would add significant cost to the construction and would experience excessive movement in extreme winds due to the low building weight above the isolators.

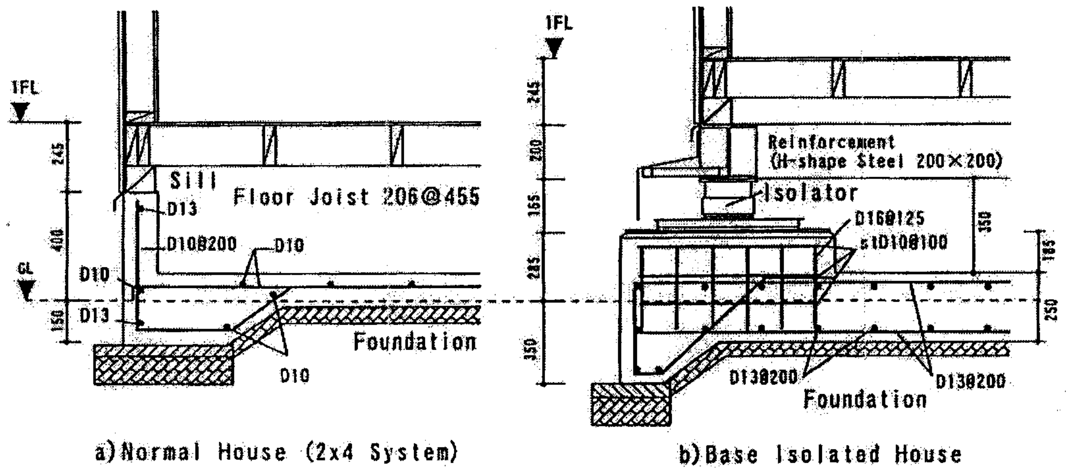


Figure 32. Section of base-isolated storey and foundation.

The authors also summarised the base isolator systems being used in Japan (Table 1). This shows a significant increase in use of building isolation over time. Rubber bearing systems dominate, but there is a trend for more innovative systems to be used. The authors present an interesting graph showing the minimum base-isolation coefficient that may be used for a given wind speed before large movement will occur. This was calculated for a medium-weight house with roof height at 7.5 m and overall plan weight of 3 kPa. This is similar to what was determined in Section 2.1.1.

Table 1. Kind and number of isolators utilised for building in Japan

Type of device	1985–1994	1995	1996	1997	Total
HDB	13	26	79	36	154
LRB	18	20	49	27	114
NRB+LD+SHD	2	14	37	24	77
LRB+NRB	4	2	21	10	37
NRB+SHD	17	0	2	0	19
LRB+SL	9	0	1	2	12
NRB+LD	4	1	2	5	12
NRB+SL	3	3	0	2	8
NRB+VD	5	1	0	0	6
Others	7	19	34	27	87
Total	**82**	**86**	**225**	**133**	**526**

LRB Lead Rubber Bearing
HDB High Damping Rubber Bearing
NRB Natural Rubber Bearing
SL Sliding Bearing
SHD Steel Hysteresis Damper
VD Viscous Damper
LD Lead Damper

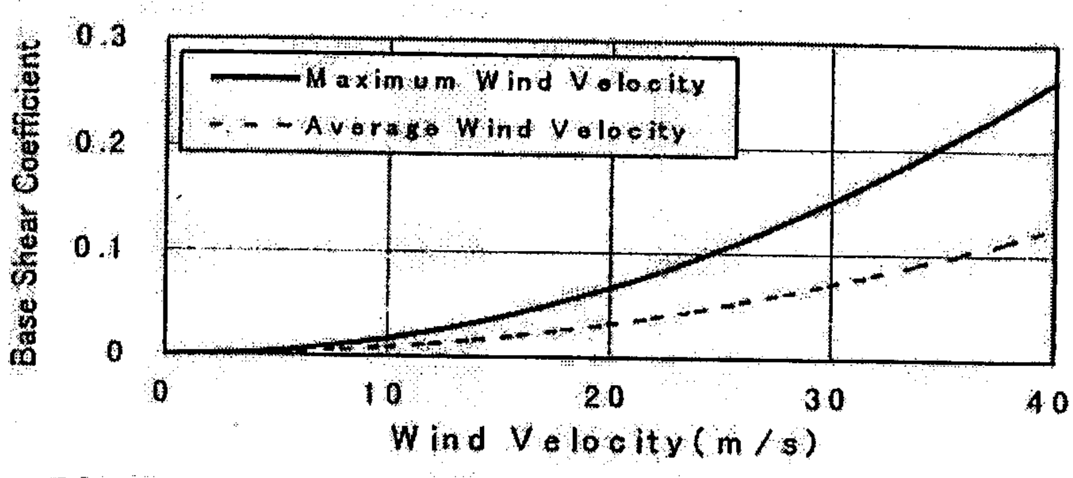


Figure 33. Relationship between minimum base shear coefficient and wind velocity.

A.2 Synthetic liners and artificial soil layers

[2] MK Yegian and U Kadakal. 2004. ‘Foundation Isolation for Seismic Protection Using a Smooth Synthetic Liner’. *Journal of Geotechnical and Geoenvironmental Engineering* 130 (11).

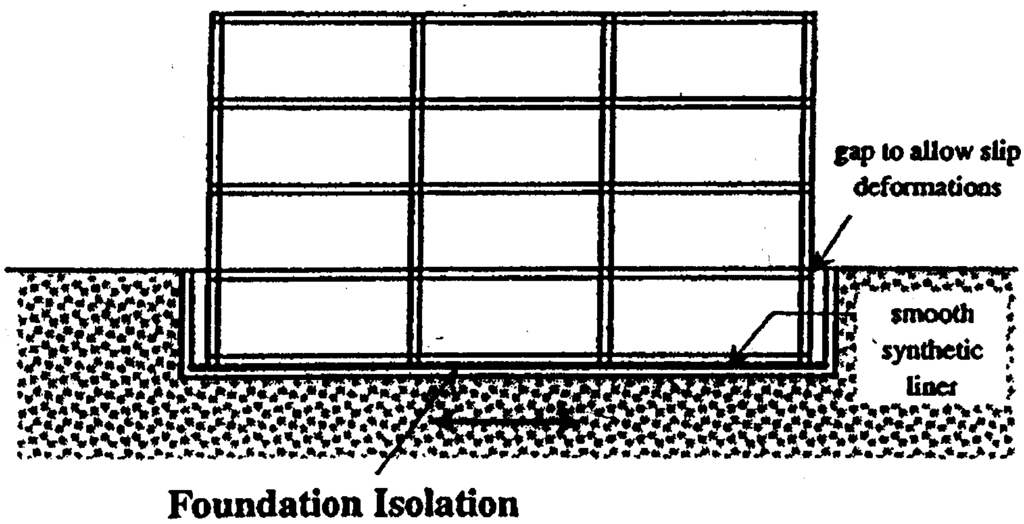


Figure 34. Foundation isolation for seismic protection of buildings using smooth synthetic liner.

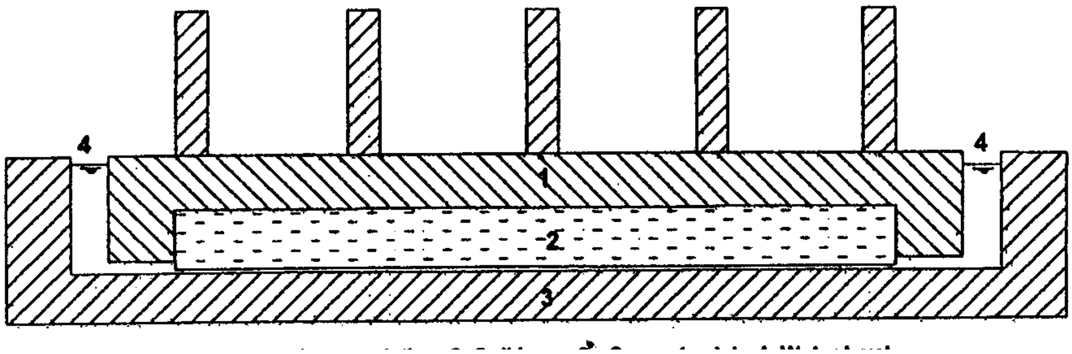
The authors proposed placing smooth synthetic materials beneath the foundation of structures as shown in Figure 34 to provide a friction base-isolating layer. Based on shake table tests, they concluded that a high strength, non-woven geo-textile placed over an ultra molecular weight polyethylene was most suitable and gave a static and dynamic coefficient of friction of 0.10 and 0.07, respectively. This coefficient was almost independent of sliding velocity and normal stress. The authors recommended more research on lining installation, introduction of a restoring force and long-term creep and environmental effects.

This system has the advantage in that the sliding surface is placed below a concrete slab and the system is therefore less likely to slide excessively in wind storms as illustrated in Figure 3. However, the authors are proposing to use site concrete, and two sliding synthetic layers followed by a base concrete slab (see Figure 34). The two concrete slab layers add cost to the building. The seismic gap between the building and bottom slab (as illustrated) will fill with water and the head of water will risk water ingress into the basement. The system proposed in reference [4] helps in this regard.

[3] IN Doudoumis, P Papadopoulos and T Papaliangas. 2002. 'Low-Cost Base Isolation System on Artificial Soil Layers with Low Shearing Resistance'. *12th European Conference on Earthquake Engineering (Paper Reference 661).*

This paper proposes interposing an artificial soil layer between the superstructure and the natural foundation soil of the buildings. This soil layer has a low shearing resistance, which allows the building to slip under the action of strong seismic motions. The reduction of the inertia forces at the superstructure, as well as the size of the expected values of the basement slippage, was investigated by analytical study.

The authors proposed the system shown in Figure 35 to avoid lateral passive reaction of the surrounding soil.



1: Foundation   2: Soil layer   3: Concrete slab   4: Water level

Figure 35. The basic concept of interposing an artificial soil layer.

The authors suggested that low shearing resistance of the interposed artificial soil layer can be provided by suitable natural materials, for example, granular products of rocks containing low friction minerals (talc, chlorite, serpentine etc), or high plasticity clays (e.g. montmorillonitic clays) or a combination of them in an appropriate arrangement. Granular rock products of this type will provide, on the one hand, a basic frictional behaviour with relatively low shearing resistance and, on the other, the required strength in compression. The shearing resistance can be reduced if a substance with 'lubrication' action is added. Wet bentonite was stated to be a natural material which presented such lubrication properties and negligible cohesion such that the overall shear behaviour could be relied upon to remain essentially frictional. Further reduction in shearing resistance can be achieved if an arrangement allowing for sliding along a pre-determined flat surface, for example a concrete slab, is used (as shown in Figure 35).

The construction shown in Figure 35 is expensive and fraught with practical problems. The constructability is dubious and the design problematic. The water levels would need to be maintained to ensure consistent slip coefficients. The presence of water creates many health, water ingress and durability hazards. The coefficient of friction proposed by the author of approximately 0.2 does not provide large force reductions from the base acceleration coefficient of 0.3 currently used in NZS 3604 house design. Much research would be needed for the material used at each site to ensure the coefficients of friction can be relied upon for the full building life.

[4] E Kevazanjian, B Hushmand and GR Martin. 1991. *Frictional Base Isolation Using a Layered Soil-Synthetic Liner System.* 3rd US Conference on Lifeline Earthquake Engineering, Los Angeles, USA.

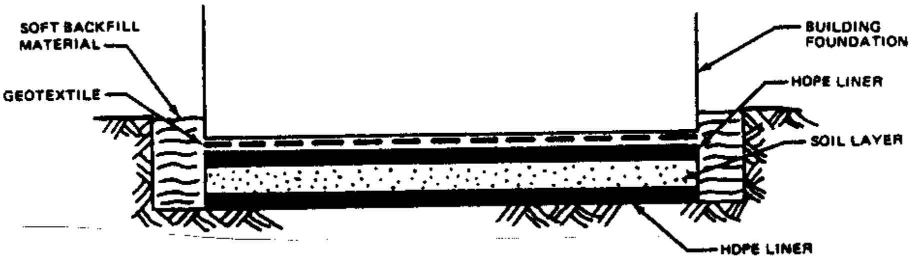
Based on shake table tests, the authors found the system in Figure 36(a) (but without the soft backfill) provided good base isolation. The authors noted that friction coefficients as low as 0.1 have been reported for the sliding resistance of geo-synthetic liner-soil interfaces, but their tests showed a large range of coefficients for the different geo-synthetic materials tested.

In the single layer synthetic liner (SLS-L) system of Figure 36(b), geo-synthetic liner material directly beneath the base of the foundation slab is placed directly in contact with a HDPE liner material placed on top of the foundation soil. The authors also proposed a layered synthetic liner-soil (LSL-S) system, where soil is placed between two geo-membranes as shown in Figure 36(a). Other possible variations on these systems include a single layer of liner material beneath the foundation slab placed directly on the foundation soil, placing multiple layers of geo-synthetic material and soil between the foundation slab and the ground and placing a layer of soil between the slab and the top of a geo-synthetic layer.

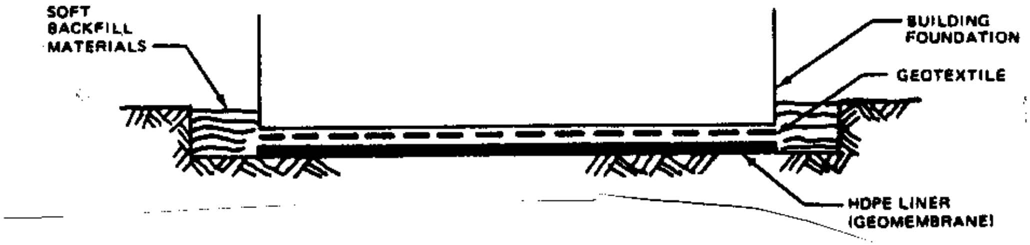
Measured static coefficients of friction varied between 0.12 to 0.22 g while dynamic coefficient of friction varied between 0.09 to 0.19 g. However, during sinusoidal tests a block (simulating a building) had accelerations varying between 0.09 to 0.40 g, depending on shaking frequency and contact pressure. Shaking table tests using El Centro records, scaled to 0.5 g, resulted in block displacement of 50-175 mm, depending on the geo-textile. The spectra from block movement showed a reduction in amplitude of approximately 40%. At longer periods the attenuation was less.

The system does not allow edge thickening to carry the building weight and waterproofing at the base edges has not been solved. Forces from passive pressure from the backfill during an earthquake make the system's effectiveness questionable. However, the system shows potential.

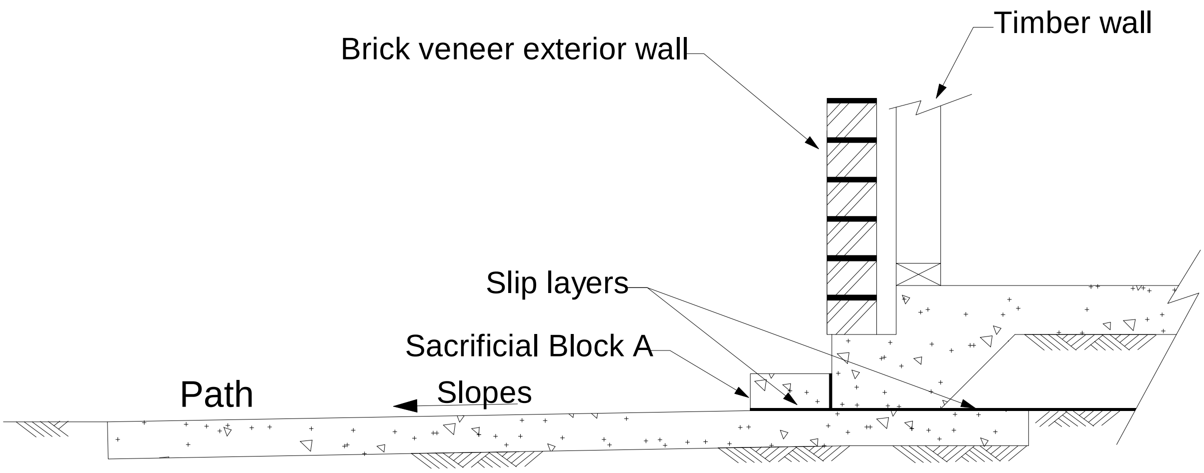
A modification to the author's proposed use is given in Figure 36(c) which would not be affected by the passive resistance of soft soils. On the edge of the building is a concrete path sloped at 1° away from the building. Part of the two sheet layer slip system is on a 200 mm wide flat portion of the path and the rest under the concrete floor slab. Steps into the building would need to slide when pushed by the building during an earthquake.



(a) Layered geo-membrane/geo-textile base-isolation system.



(b) Pure frictional geo-membrane/geo-textile base-isolation system.



(c) The proposed system.

Figure 36. Application of synthetic liner base isolation.

[5] H Xiao, JW Butterworth and T Larkin. 2004. *Low-Technology Techniques for Seismic Isolation.* 2004 NZSEE Conference.

The authors proposed using a low friction layer beneath the foundation to act as a base-isolation layer – but only for heavy construction using weak building materials. The proposed construction method is shown in Figure 37. Suggested isolation materials with corresponding friction levels as measured are given in Table 2. For pebbles the underside layer is a polythene membrane.

Water getting into the gap adjacent to the foundation would be a problem for many reasons. The thickness of the floor slab shown in Figure 37 is large and therefore expensive. However, stepping as proposed in Figure 36 would provide economies. If used for brick veneer, masonry or timber-framed walls, rather than a concrete wall construction sketched by the authors, moisture ingress at the base of the wall is likely to be a problem.

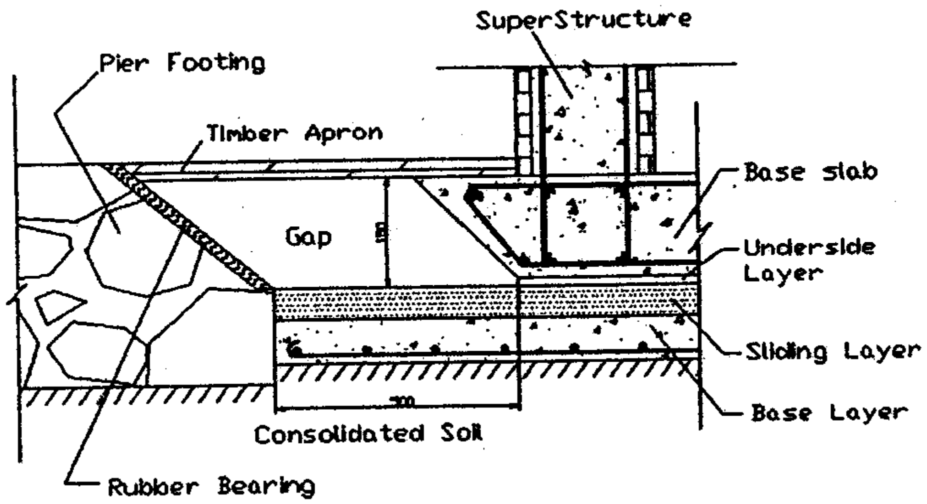


Figure 37. Proposed construction method

Table 2. Isolation level

Material	**Isolation level (g)**
Pebble (6-8 mm)	0.20
Polythene membrane	0.18
Polypropylene sheet (0.8 mm)	0.15
Polyvinyl chloride sheet (1.0 mm)	0.10

[6] MK Yegian and AM Lahlaf. 1992. 'Dymanic Interface Shear Strength Properties of Geomembranes and Geotextiles'. *Journal of Geotechnical Engineering* 118 (5).

Shake table and slope tests as per Figure 38 were performed to measure the dynamic interface properties between a geo-membrane and geo-textile. The coefficient of friction was found as per Figure 39.

The measured coefficient of dynamic friction was 0.18 for the dry condition and 0.15 for the wet. The geo-membrane was Gandle HD60, hard, smooth HDPE and the geo-textile was Polyfelt TS700, non-woven, continuous filament, needle-punched. This limited the interface accelerations to between 0.2 and 0.24 g. The geo-membrane to geo-membrane interface friction was 0.13.

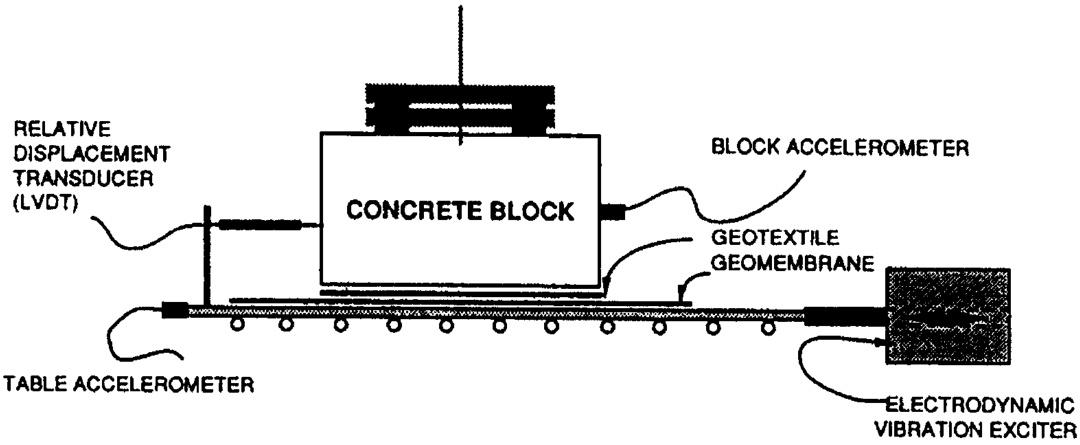


Figure 38. Shaking table facility.

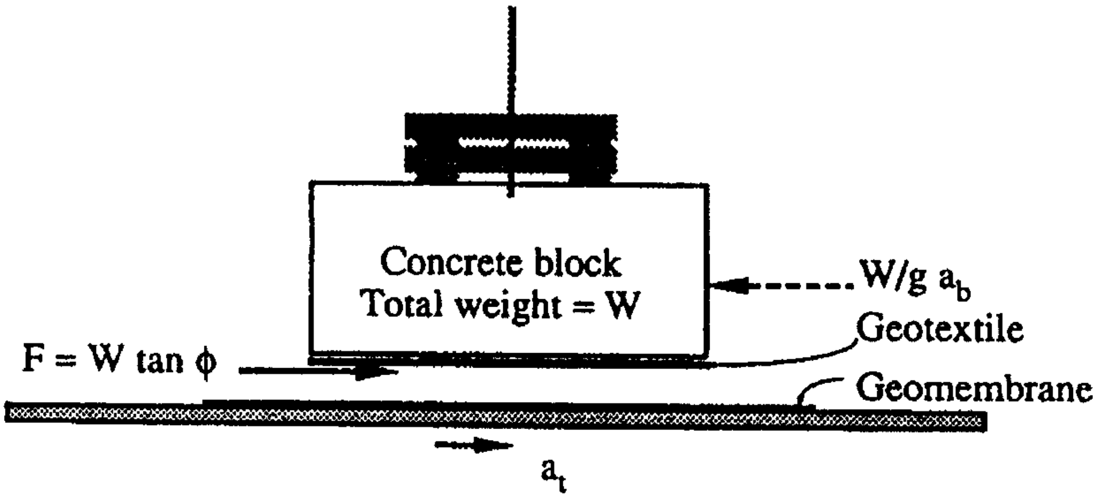


Figure 39. Free-body diagram of block.

[7] MK Yegian and M Catan. 2004. ‘Soil Isolation for Seismic Protection Using a Smooth Synthetic Liner’. *Journal of Geotechnical and Geoenvironmental Engineering* ASCE (Nov): 1131.

The authors proposed using a synthetic liner consisting of a non-woven geo-textile over an ultra-high molecular weight polyethylene geo-textile/UHMWPE, placed within a soil profile to dissipate seismic energy transmitted to the overlying soil layer and structure (Figure 40). For typical normal stresses in the proposed application, the coefficient of friction at the interface of these materials was measured as 0.06 and this was independent of sliding velocity. This concept of soil isolation was considered to be an effective and inexpensive way of reducing seismic ground motions through slip displacements. Shaking table tests on soil layers isolated using synthetic liners were conducted using harmonic and earthquake base excitations. The results showed that an isolation liner can significantly reduce the accelerations at the surface of the isolated soil mass (see Figure 41). Accompanying such a reduction in accelerations are slip displacements that manifest around the perimeter of the isolated soil. Because of the curved nature of the liner, permanent slips are minimised by the restoring effect of the gravitational forces of the isolated soil mass. Analytical results under field scale conditions indicated that a soil isolation liner can dramatically reduce the peak and spectral accelerations and thus provide seismic protection to a structure founded on soil-isolated ground (see Figure 42). The theory showed that the maximum transmitted acceleration as a ratio of ‘g’ started to approach the coefficient of friction of the geo-textile/UHMWPE interface for large plan buildings, with shallow depth foundations at H/D ratios greater than 6 as shown in Figure 43. (H = horizontal dimension of isolated soil and D = depth to liner.)

One problem associated with this solution is that rainwater captured between the building edge and liner edge is confined and cannot drain freely. The thickened bottom slab edges at building edges and waterproofing at this point needs careful consideration. A solution for these problems is shown in Figure 44.

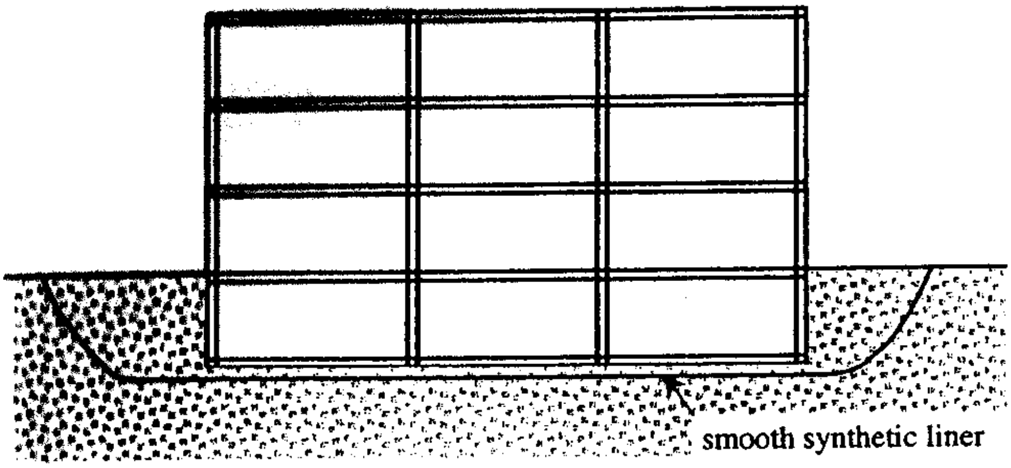


Figure 40. Soil isolation for buildings.

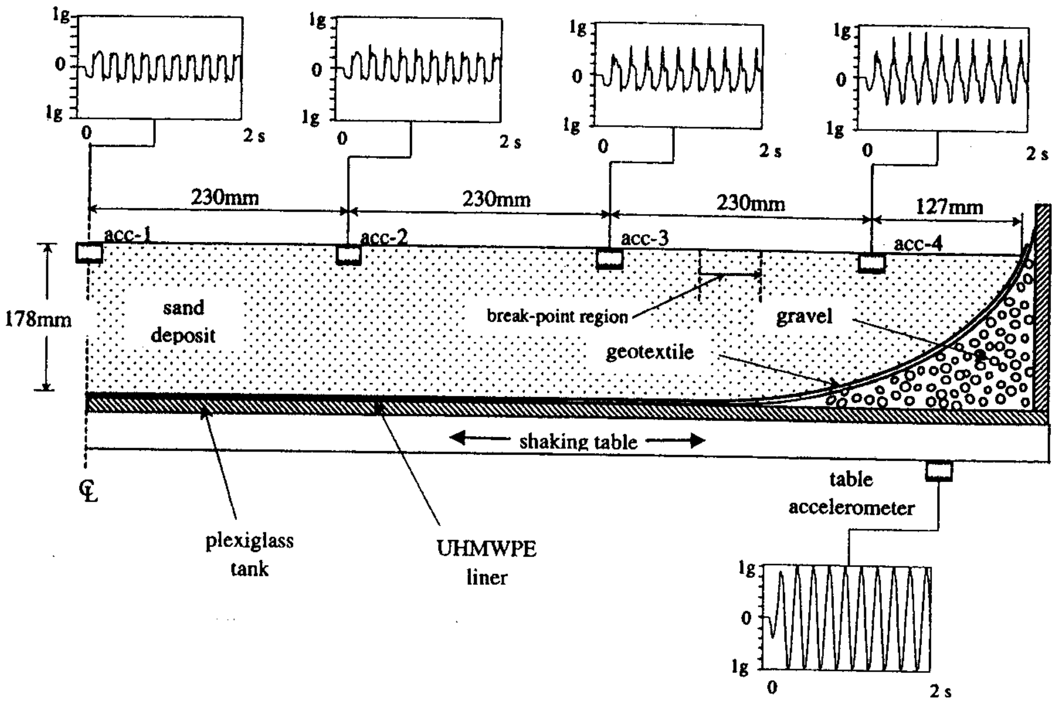


Figure 41. Acceleration records from shaking table tests on tub-shaped isolated soil subjected to a 5 Hz harmonic motion.

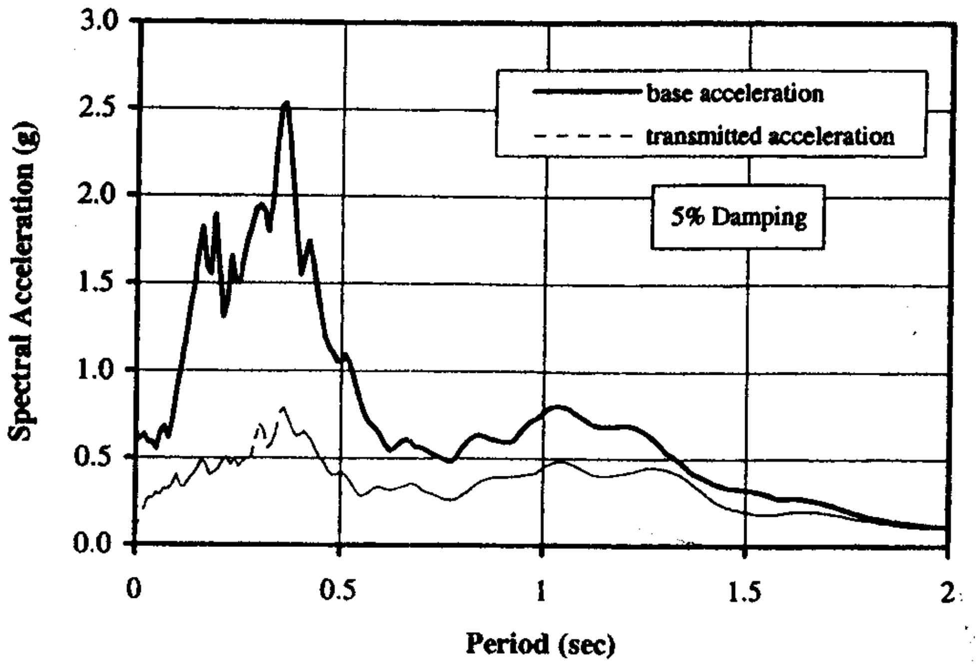


Figure 42. Base and transmitted acceleration response spectra of cylindrical-shaped isolated soil (H = 60 m, D = 3 m) using the Santa Cruz record scaled to 0.6g.

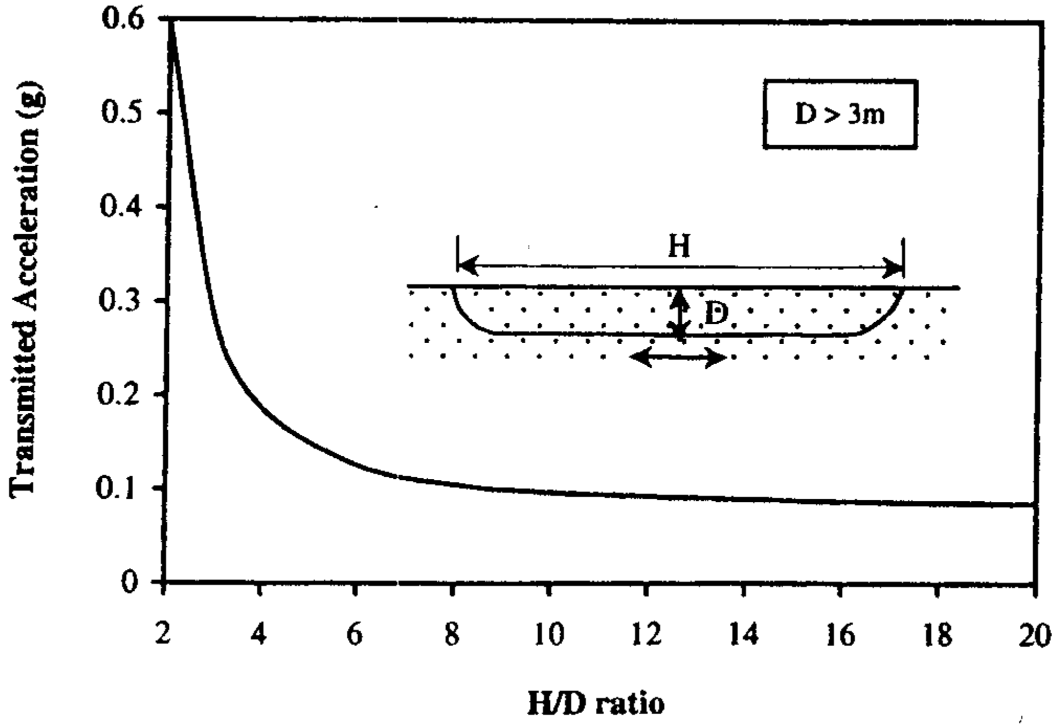


Figure 43. Transmitted acceleration as a function of H/D ratio computed analytically using 2 Hz cyclic shaking, with 0.6 g base acceleration amplitude.

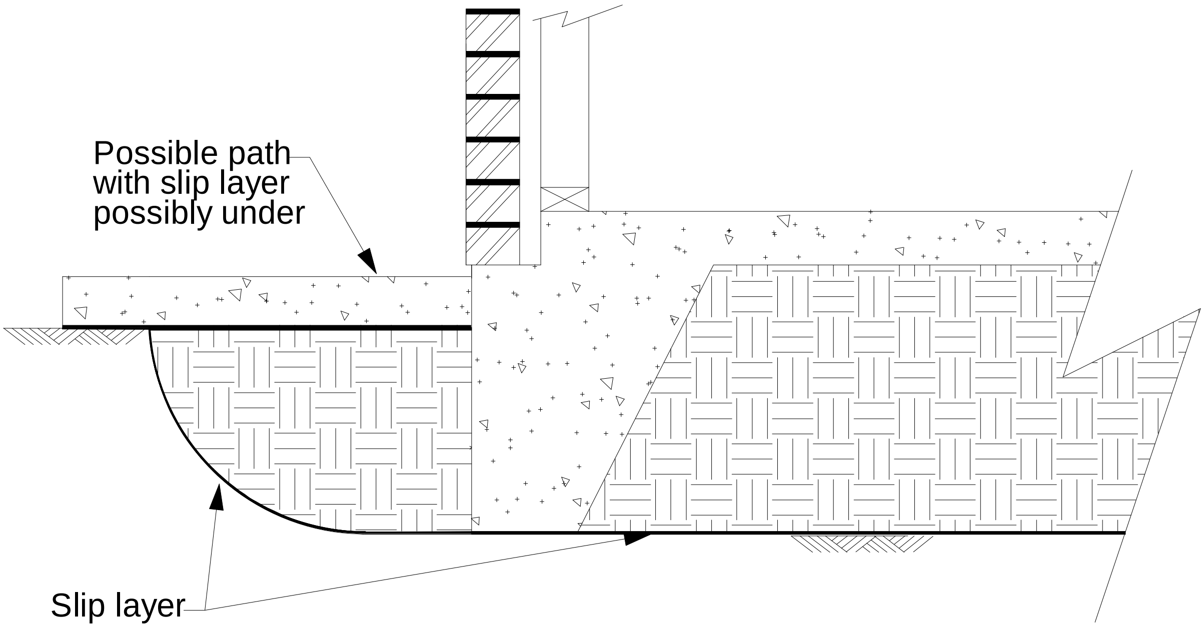


Figure 44. Variation of the system proposed by report authors.

A.3 Friction based isolation systems

[8] WH Robinson, CR Gannon and J Meyer. 2006. 'The RoGlider™ – A Sliding Bearing With An Elastic Restoring Force'. *Bulletin of the New Zealand Society of Earthquake Engineering* 39 (1).

The RoGlider™ is a sliding bearing which includes an elastic restoring force. The RoGlider™ either is a double acting unit with the restoring force provided by two rubber membranes (Figure 45), or a single acting unit.

The double acting RoGlider™ consists of two stainless steel plates with a PTFE ended puck sitting between the plates. Two rubber membranes are attached to the puck with each being joined to the top or bottom plates. When the top and bottom plates slide sideways with respect to each other, diagonally opposite parts of the membrane undergo tension or compression. The tension components provide the restoring force between the plates. A typical set of hysteresis loops is shown in Figure 46.

A typical RoGlider™ may have a maximum displacement of ±600 mm, a maximum vertical load of 1 MN, with an outside diameter of ≈900 mm and a coefficient of friction at ≈0.5 m/s of ≈11%.

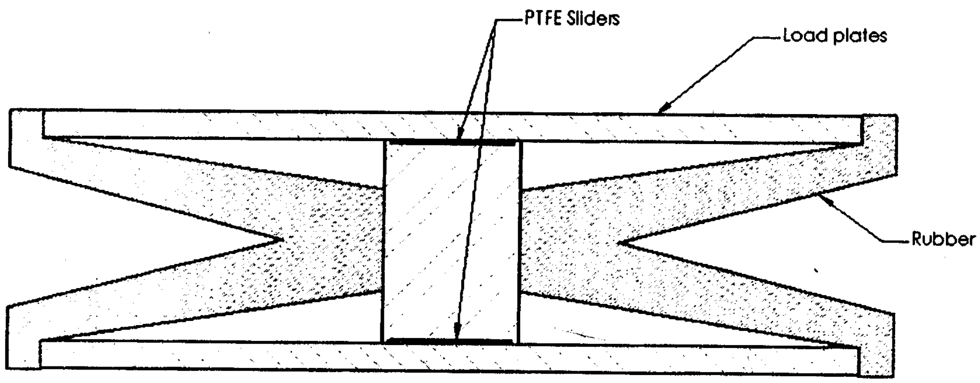


Figure 45. RoGlider section.

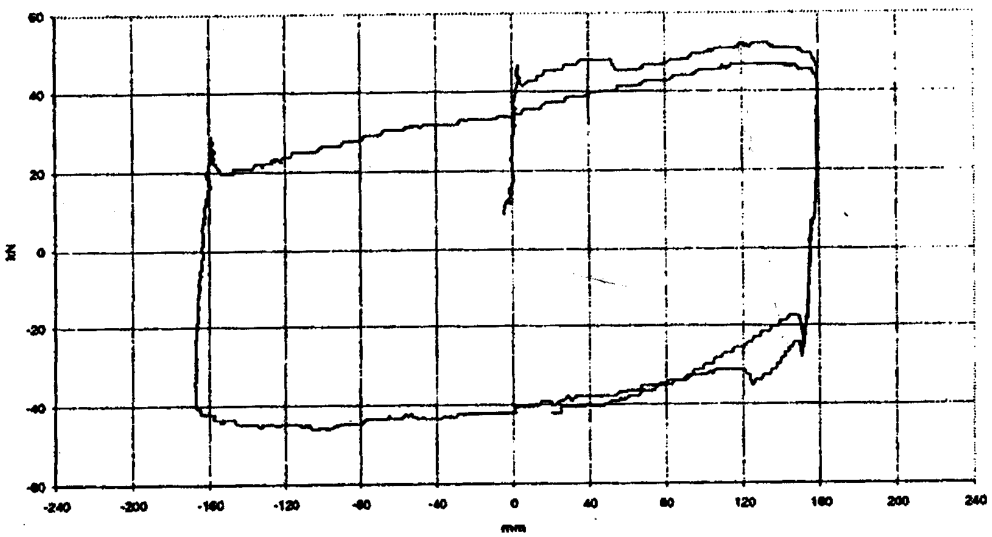


Figure 46. RoGlider force displacement curve – vertical force of 850 kN.

[9] WH Robinson, CR Gannon and J Meyer. 2006. 'A Roball With An Elastic Restoring Force'. *Bulletin of the New Zealand Society of Earthquake Engineering* 39 (1).

The top and bottom surfaces of the rubber container are flat and the sides are curved as illustrated in Figure 47. It contains seven solid balls. Other designs of the RoBall™ suitable for larger displacements could include 13, 19, 25 or more solid balls in close packed arrays.

The sides of the RoBall may be made thicker than the top and bottom surfaces, thereby contributing to a restoring force for small displacements (Figure 48), while for large displacements there is cyclic restoring with a force-displacement wavelength approximately twice the diameter of the RoBall (Figure 49).

The rolling action of the RoBall means that the device itself has no displacement limit and so the maximum displacement is limited only by installation requirements. The dynamic behaviour of the device is independent of both frequency and ambient temperature within ranges that are applicable to most practical installations. The effective friction coefficient is ≈0.1.

The applications for the model of the RoBall containing solid spheres are expected to be for protecting light equipment and light structures from mechanically generated or earthquake-induced vibrations.

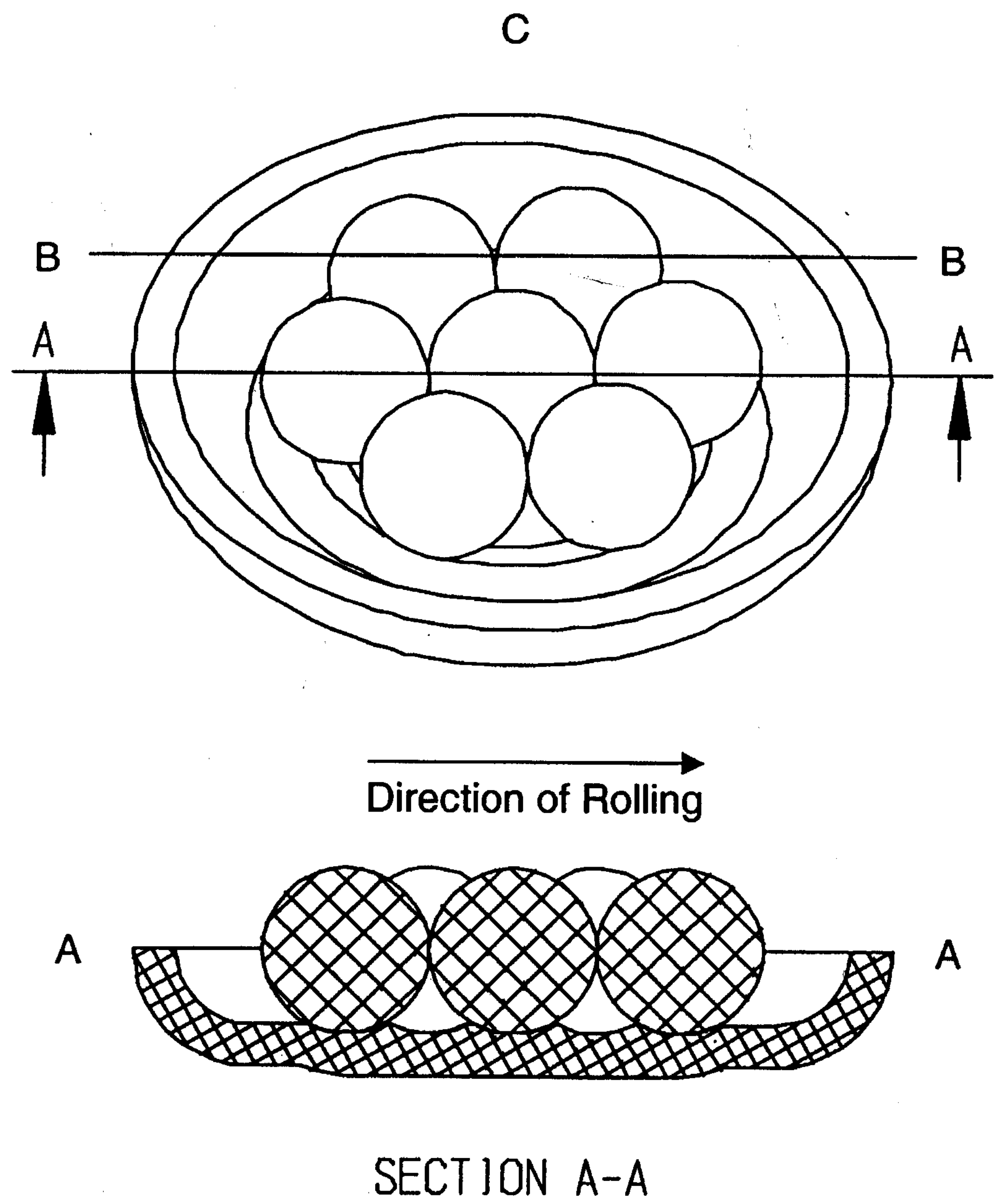


Figure 47. A seven-ball RoBall.

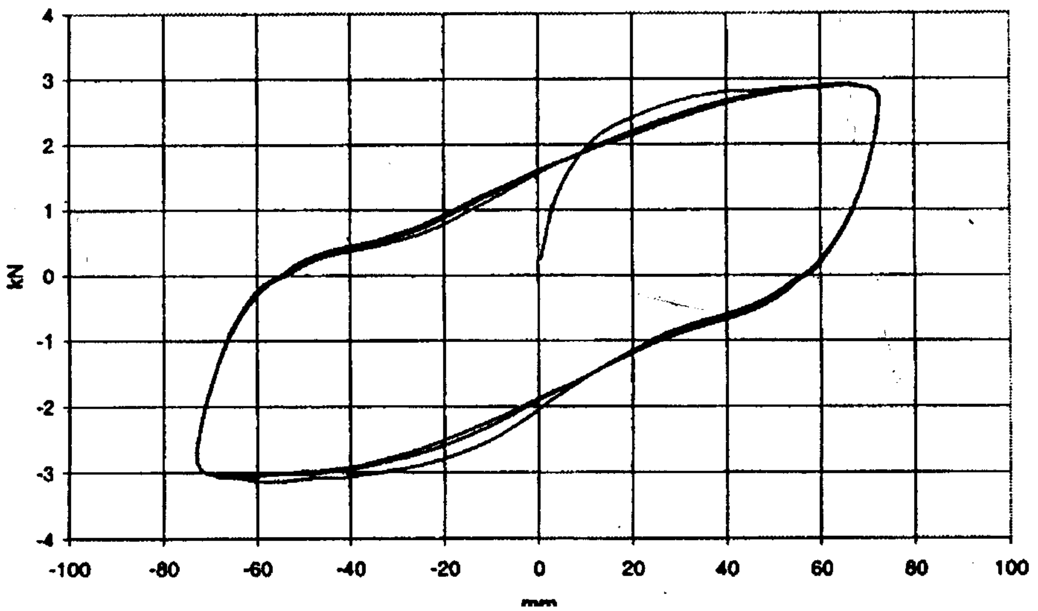


Figure 48. RoBall – small displacement showing the restoring force characteristic.

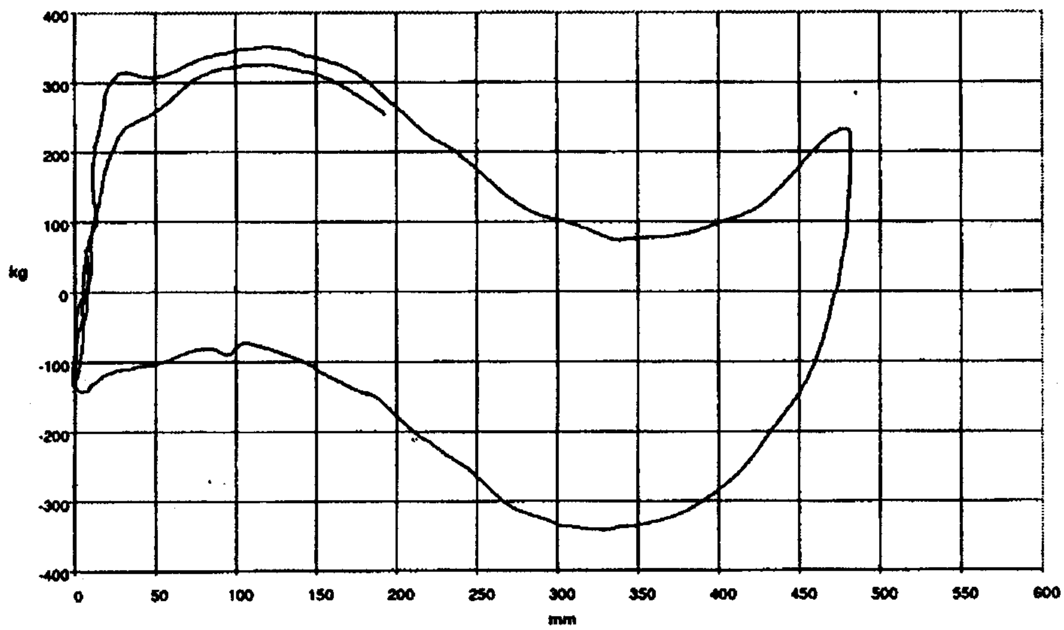


Figure 49. RoBall – large displacement with cyclic shear forces.

[10] MO Moroni, M Sarrazin, J Brull and R Muňoz. 2004. 'Shaking Table Tests of a Scaled Base Isolated Shear Wall Building'. *Proceedings of the 8th US National Conference on Earthquake Engineering (Paper No. 728).*

A series of laboratory tests were performed on a scaled model of a four storey shear wall building equipped with seismic isolators. Two kinds of bearings were used; high damping rubber and sliding pads. The sliding bearings presented the largest reduction in peak acceleration. The peak acceleration in the model with sliding bearings was 30-50% less than for fixed condition. Analytical models were developed that predicted the dynamic characteristics with reasonable accuracy.

The sliding pad friction bearings consisted of a Teflon sheet that slid on a polished stainless steel plate. The friction coefficient varied from 0.11 to 0.16 for the lubricated and non-lubricated conditions, respectively. Levelling screws were used in the assembly. Two rubber pads provided restoring forces.

A.4 Combined isolation systems

[11] W Shi, H Sun and Q Wang. 2004. 'A Study on Combined Isolation System'. *13th World Conference on Earthquake Engineering, Vancouver BC, Canada (Paper No. 2232).*

This paper proposes using a mixture of conventional rubber bearings and sliding rubber bearings (SRB) to isolate a building.

Laminated rubber bearings (LRB) and SRB provide suitable horizontal flexibility, but because of the vertical strength limit, too many bearings in an isolation system lead to a lateral stiffness which is too high. Sliding rubber bearings possess high vertical initial stiffness and very low post yielding stiffness, which would cause unacceptably large displacements of structures after sliding occurs and residual displacement after earthquake. The author proposed using a so-called combined isolation system (CIS) composed of LRB and SRB in order to satisfy serviceability under lower intensity earthquakes and wind loads, and response reduction under strong earthquakes. It was claimed that a cheaper, better solution was obtained.

A.5 Field testing of isolated buildings

[12] F Braga and M Laterza. 2004. 'Field Testing of Low Rise Base Isolated Building'. *Engineering Structures* 26 (2004): 1599-1610.

A series of dynamic snap-back tests were carried out on a residence building (Figure 50 to Figure 52) in southern Italy. The aim of the research was to investigate the seismic behaviour of low rise base-isolated structures mounted on rubber bearings only, or using a hybrid isolation system (sliding bearings for isolation and steel rubber bearings to have a re-centring force).

High initial displacements (up to 170 mm) were reached using a reusable mechanical device and a 200 tonne reaction wall.

The paper presents the experimental study performed and its main results. As there were two twin buildings, one isolated and one not, the response in future earthquakes (particularly regarding non-structural damage) will be of interest.

Each of the 28 bearings used in the base-isolation system of Building 'A' was a package including a slider (steel-teflon bearing with about 4-5% of friction coefficient) mounted on top of an HDRB. The device can work alternatively as a rubber isolator or a slider by simply locking the upper part or the lower part, respectively (Figure 52).

In this way, two different isolation systems were obtained: the first one using only the HDRBs; and the second using some bearings in which the sliders are unlocked and the elastomeric part is locked and others, for re-centring capabilities, in which the sliding part is locked and the elastomeric part unlocked.

Tests on the hybrid system were performed using 12 HDRB and 16 sliders. The relative number of HDRBs and sliders was fixed to obtain a natural first isolated mode period of 2.0 s.

Experimental data confirmed good experimental behaviour for the two isolated structures, especially for the hybrid one. Hybrid isolation can be very effective in overcoming typical design problems connected with the use of HDRB systems only, such as instability, extremely low stiffness for low rise buildings, vertical dimensions in the seismic gap etc.

The in-parallel use of mixed systems permits decoupling of stiffness and energy dissipation, especially when the re-centring action is offered by elastic devices like low damping rubber bearings (LDRB).

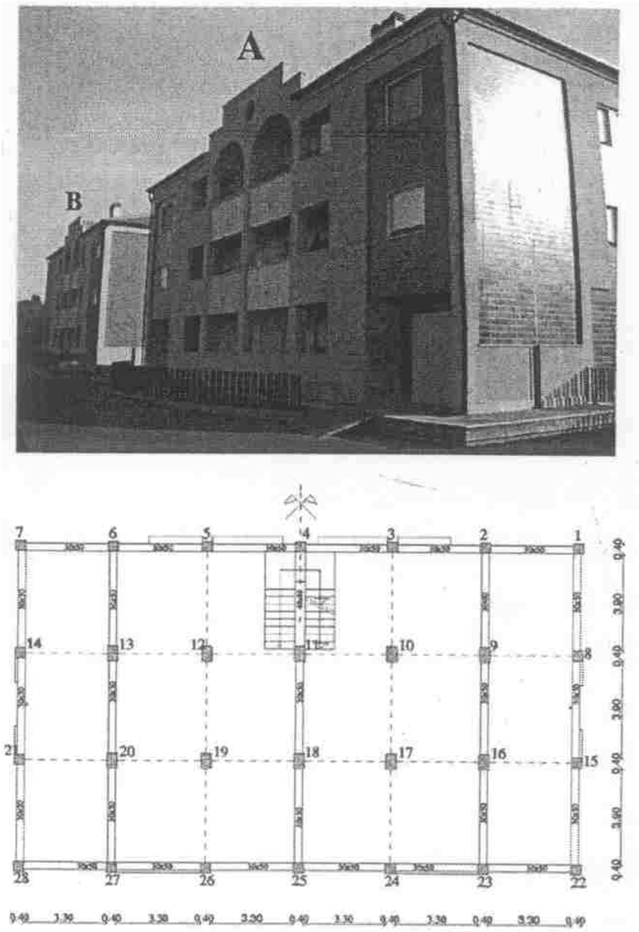


Figure 50. The twin buildings (fix base 'B' and base-isolated 'A') and layout of typical floor.

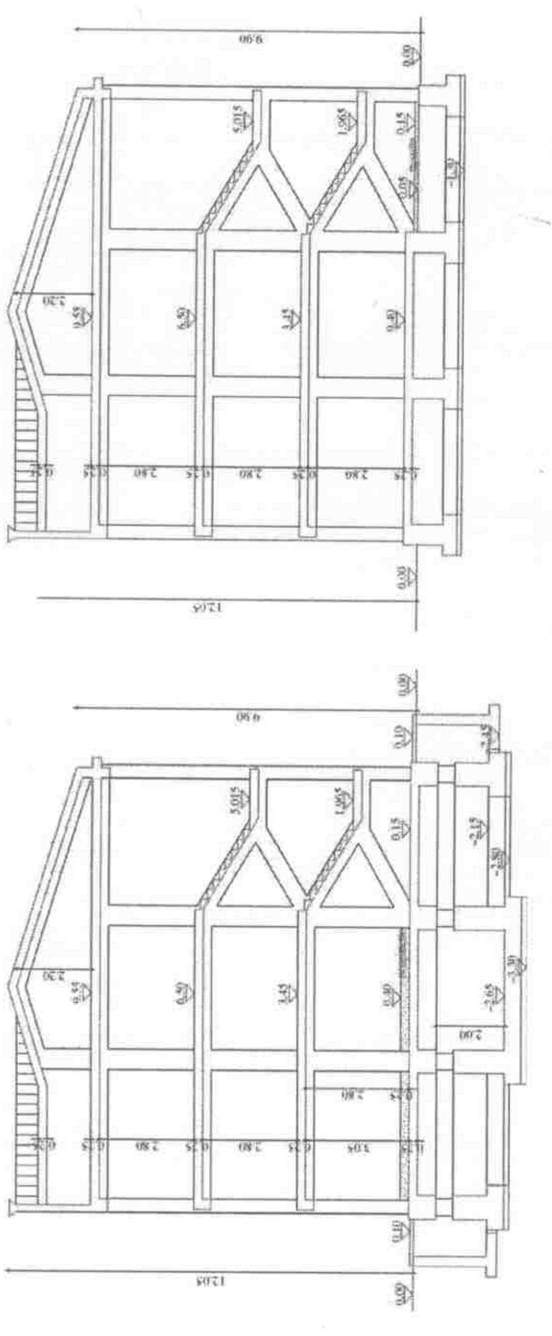


Figure 51. Transverse sections of twin buildings.

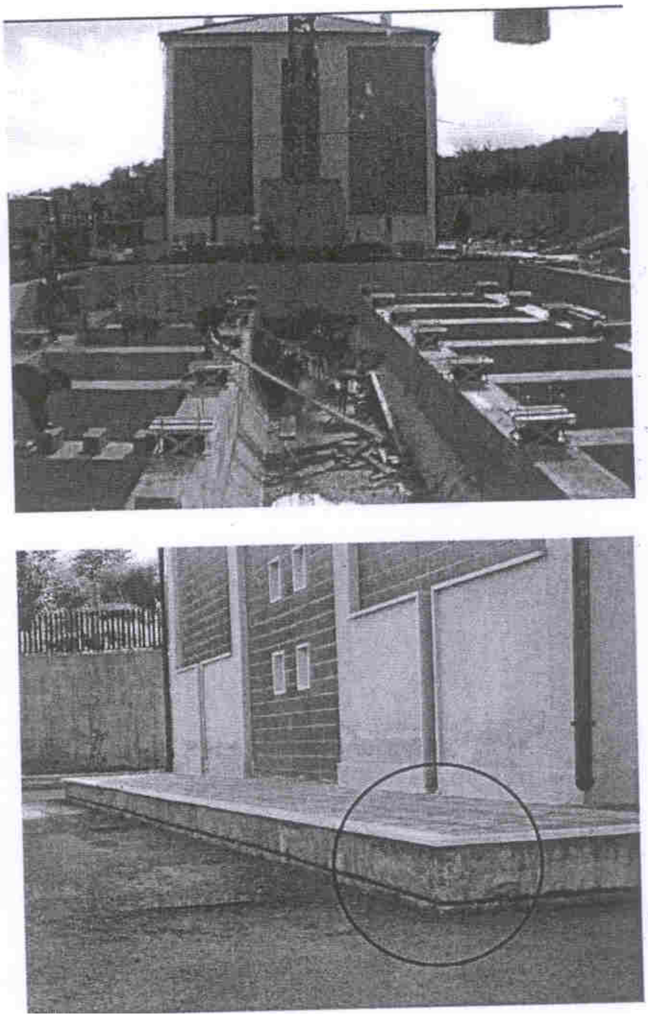


Figure 52. Foundation of building ‘A’ and vertical gap for isolation.

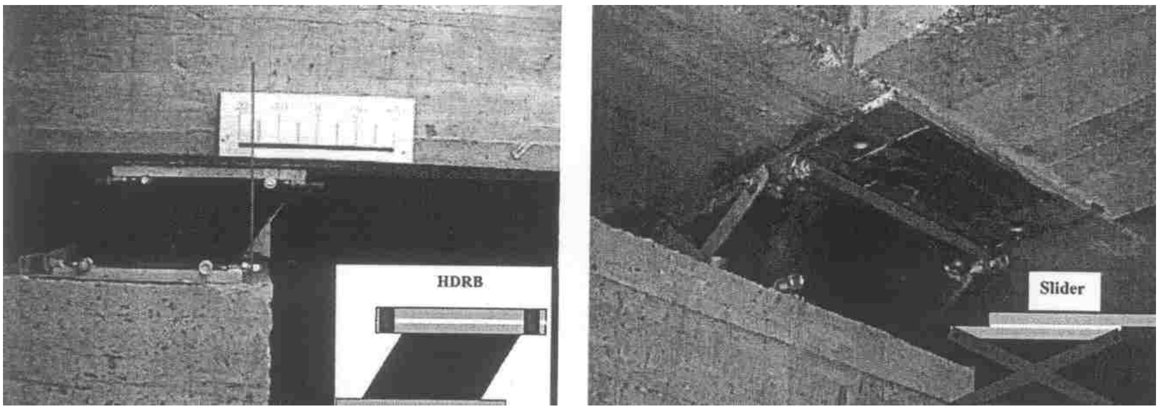


Figure 53. Special mixed bearing used like HDRB (a) or like slider (b).

A.6 Isolators beneath masonry walls

[13] Lee Li. 1987. ‘Advances in Base Isolation in China’. Book Title: *Developments in Geotechnical Engineering (Vol. 43).*

The author discusses new ideas for base isolation of buildings in China, but states that few have been adopted.

The first isolated building constructed was achieved by forming a terra plate and placing a thin layer of rounded uniform sand particles on it, and then covering with another terra plate and building the walls above as shown in Figure 54. This does not appear to be a very practical solution for New Zealand application and would have limited seismic movement before instability. However, the author states that five buildings were constructed this way in China.

The author then discusses rubber pads used above bridge piers or on the tops of columns below the roofs. However, the movement capacity of these pads is only 30 mm.

Another base-isolation method discussed was rocking columns with rounded tops as shown in Figure 55. This construction may be suitable for timber floors, but is unlikely to be suitable for masonry construction. This construction is unstable under wind loading and the author proposed using several options of breakers to give resistance under wind, but not earthquake, loading. The breaker systems proposed are likely to be impractical for New Zealand conditions.

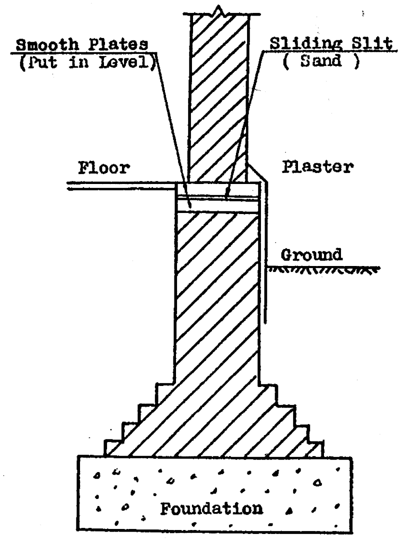


Figure 54. Concept for base isolation.

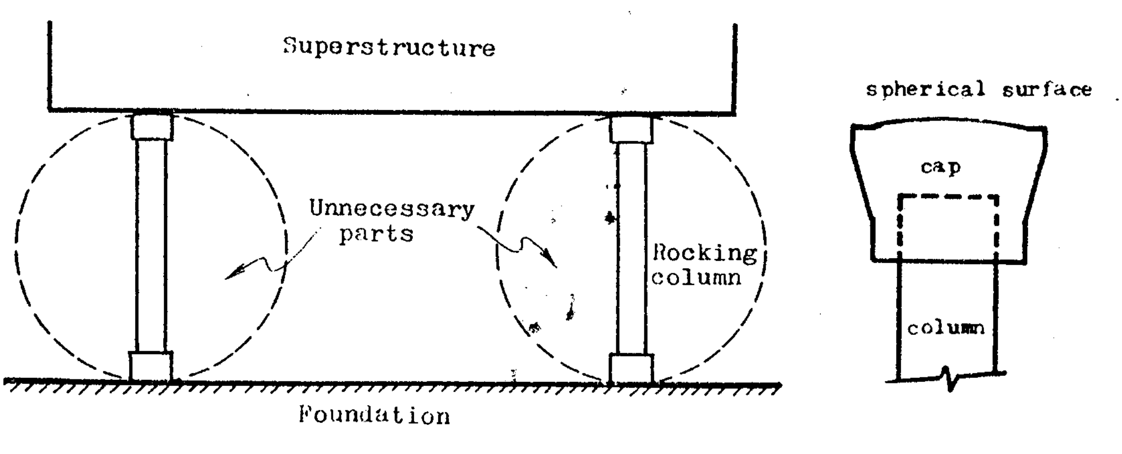


Figure 55. Rocking columns.

Other systems discussed were:

(1) using a layer of soil between column footing and pile head,

(2) using a curved steel plate between foundation and column footing which deforms plastically under lateral load, and

(3) mass tuning.

[14] X Chen. 2004. 'Behaviour, Analysis and Application Research for Treated Asphalt-Fibre Seismic Isolation Cushion'. *13th World Conference on Earthquake Engineering, Vancouver BC, Canada, August 2004: 1-6 (Paper No. 1959).*

The author stated that prior to the year 2001, more than 300 buildings had been constructed in China using base isolation for which the mechanism was mainly lead core laminated steel plate rubber bearings. Of these, two seven storey masonry concrete residential trial buildings isolated with BS cushion (treated asphalt-fibre seismic isolation cushion) were built in Hangzhou, China. The fibre replaces the steel plate and the asphalt the rubber in conventional laminated steel plate rubber bearings. One building was isolated by replacing some depth of base soil under a mattress foundation with an alternative setting of four layers of BS cushion and four layers of sand. The fundamental period of this building was elongated from 0.3 s to 1 s. (The period of the non-isolated building was determined from a similar building.) Due to the huge area application of BS cushion in the isolated building, the construction cost rose considerably.

The paper mainly discussed another building where only one layer of 20 mm thickness of BS cushion was used to separate all the bearing walls and strip foundation walls (Figure 56 and Figure 57). Due to the small area application of BS cushion in this project, the construction cost of this building did not rise significantly compared to non-isolated buildings.

However, from the author's data it appeared that the maximum movement over the depth of the isolation layer was 20 mm before a ground slab stop was hit. The impact force when this happened did not appear to have been considered. The seven storey building was analysed as being rigid in a single D.O.F. model where 30% damping was assumed. These assumptions seem dubious and still only reduced the earthquake forces on the building by 36% according to the author's analysis.

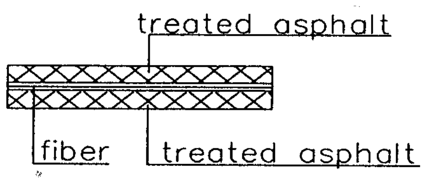
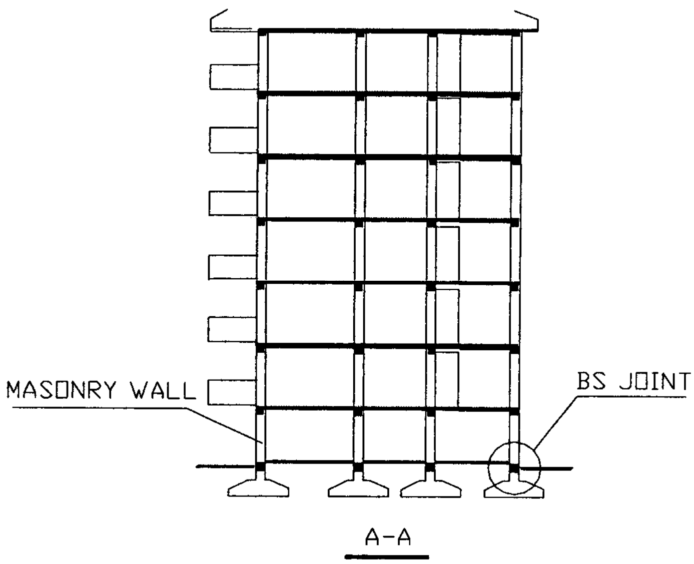


Figure 56. Cross-sectional view through BS cushion.



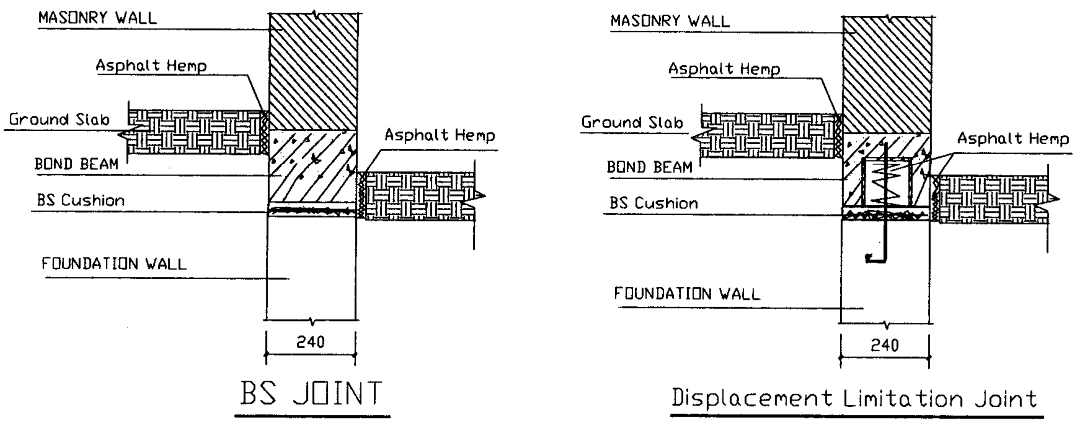


Figure 57. Use of the BS layer in the structure.

[15] M Sassu, G Mariani and D Mattafirri. 2004. 'Mechanical Behaviour of Simple Masonry Buildings With Low-Cost Dissipators Distributed Throughout the Basement'. *13th World Conference on Earthquake Engineering, Vancouver BC, Canada (Paper No. 3397).*

The proposed base dissipation system, named RCW dissipater, consisted of a single layer of mortar of modest mechanical properties, resting on an elastomer waterproofing sheath set between the foundation and the base of the masonry wall to be isolated. Both layers were fitted with a series of vertical metal rods anchored to the foundation casts and the belt course of the wall base (Figure 58). This resulted in a rigid connection between the foundation and the superstructure, which the author stated would detach the structure from the ground in the event of violent quakes.

The authors stated that the damp-proof course would maintain its integrity in the presence of small seismic actions, but would crack and dissipate mechanical energy in the event of high-intensity earthquakes.

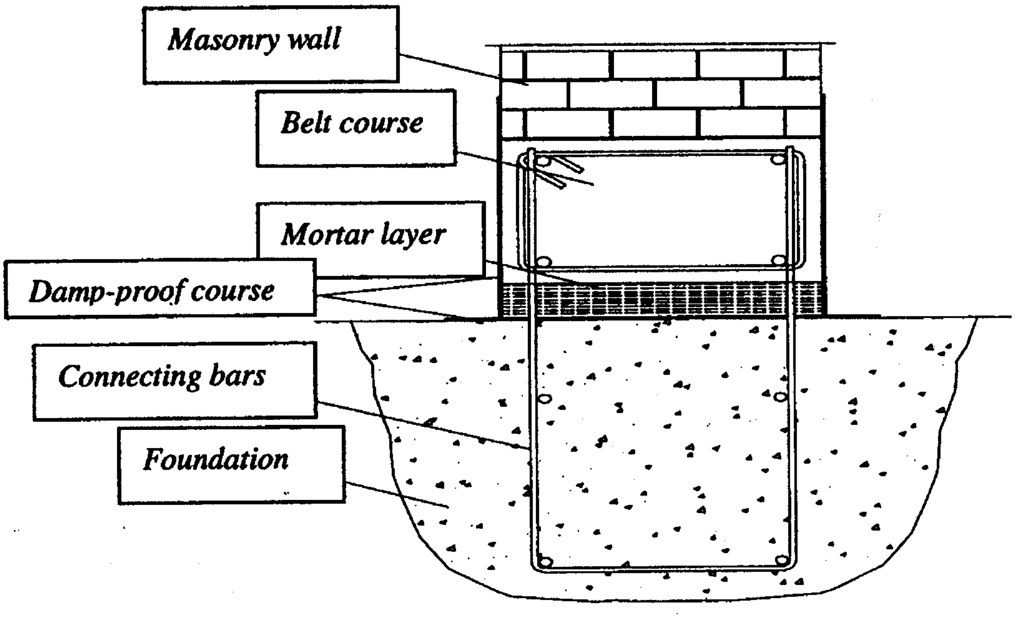


Figure 58. The proposed RCW base dissipator.

It is considered that this base-isolation system would have inadequate slip movement potential to be effective. Others have proposed similar systems, but without the connecting bars.

[16] AS Pall and R Pall. 1991. 'Seismic Response of a Friction-Base-Isolated House in Montreal'. *6th Canadian Conference on Earthquake Engineering, Toronto, Canada, 1991.*

The author's abstract stated:

"A two-storey residential house, incorporating friction-base isolators, was built in Montreal. Three-dimensional non-linear time-history dynamic analysis was chosen to determine the seismic response of the structure. Compared to conventional construction, the stresses and accelerations in a friction-base isolated building are dramatically reduced, thereby the damage to the building and its contents is minimized. The friction-base isolators are simple in construction and need no maintenance, repair or replacement over the life of a building. The low cost of friction-base isolators suggests wide application in low rise construction including residential houses."

Figure 59. Front view of house.

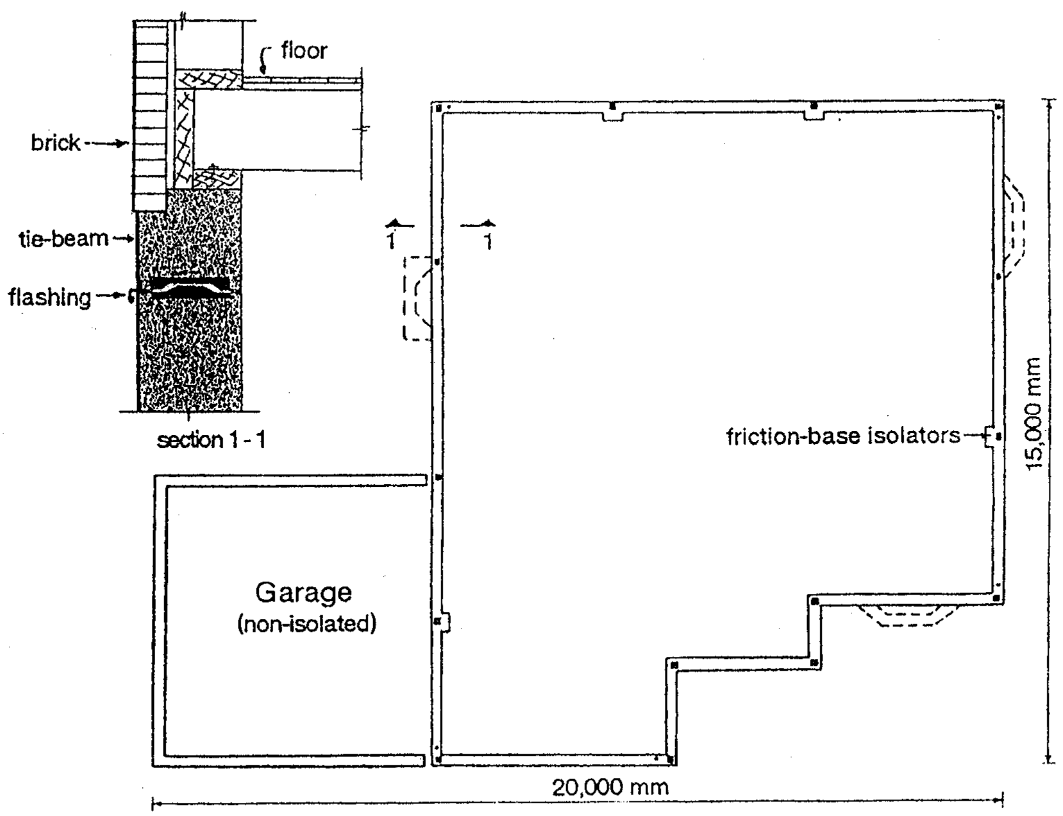


Figure 60. Location of friction-base isolators – plan.

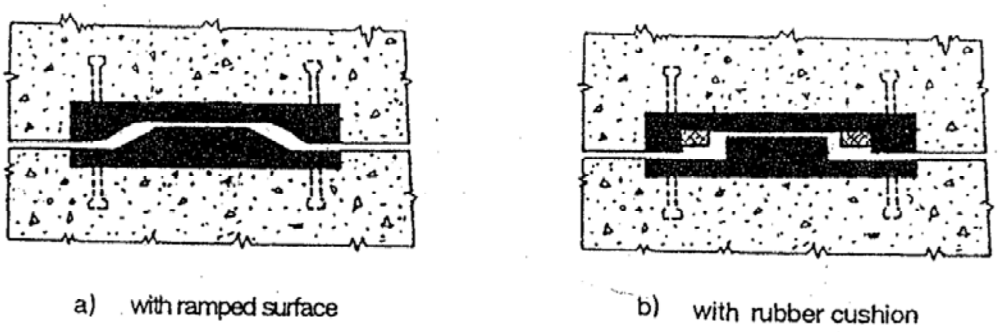


Figure 61. Detail of friction-base isolator.

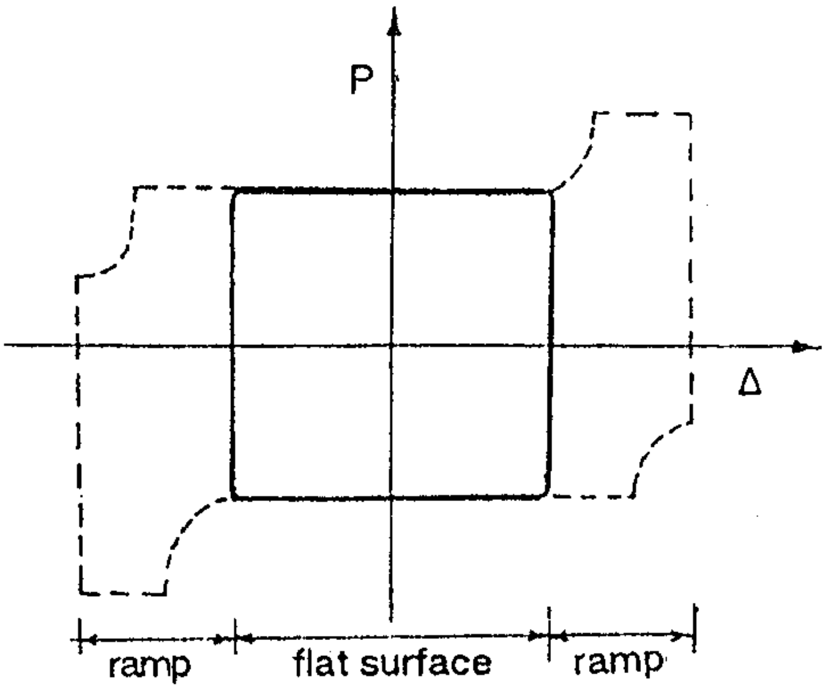


Figure 62. Hysteresis loop of friction-base isolator (with ramped surface).

Details of the house and base-isolation system are shown in Figure 59 to Figure 61. The building had interior columns which were 'pinned' top and bottom to accommodate a displacement of 25 mm. The ramp surface in the isolator was designed to increase the resistance after 25 mm movement. However, neither this nor the impact forces at the rubber cushion stop when the allowed 25 mm movement was exceeded was considered by the authors in their analysis. The additional forces from the slope of the ramp, and impact from the rubber cushion, may lead to greater damage to the building and contents than might occur in an non-isolated building.

The authors stated that if they had used a rubber pad isolator the expected movement in the design earthquake would have been 150-180 mm, whereas in this friction device the design movement was only 25 mm. This is considered dubious, particularly as graphs by the authors showed building accelerations were reduced by 70% due to the isolation.

Limited details of the friction isolators were given, but it appeared to be a steel plate to steel plate interface. The coefficient of friction assumed was 0.2. It is considered that house torsion and 'binding' of the system would need to be considered carefully.

For earthquake perpendicular to the wall in Section 1-1 of Figure 60, the force across the isolator = 0.2P where P is the axial load. These walls are unlikely to be able to carry the bending movements associated with this force (see Section 4.1.2). In fact as the wall is effectively pinned at the floor level and isolator level (and maybe at the base of the wall) it will form a mechanism under large seismic loads – which is clearly unsatisfactory. Corner effects would also need careful consideration. The problem of residual deflection across the isolator after the earthquake has stopped also needs consideration. It is surprising that this wall system has been build and accepted by the local authorities.

[17] M Qamaruddin, SK Al-Oraimi, KS Al-Jabri. 1996. **‘**Worldwide Development of Friction Seismic Isolation Scheme for Masonry Buildings’. *11th World Conference on Earthquake Engineering (Paper No. 559).*

The paper presents a review of the worldwide development of friction seismic isolation (FSI) scheme for masonry buildings where the isolation mechanism was purely sliding friction. Shaking table tests were performed on brick house models using different sliding materials which were interposed between the superstructure and substructure. The results suggested significant reduction in floor accelerations. Further, comparisons showed a good general agreement between experimental and theoretical results. Four demonstration brick buildings were built in China using the FSI scheme.

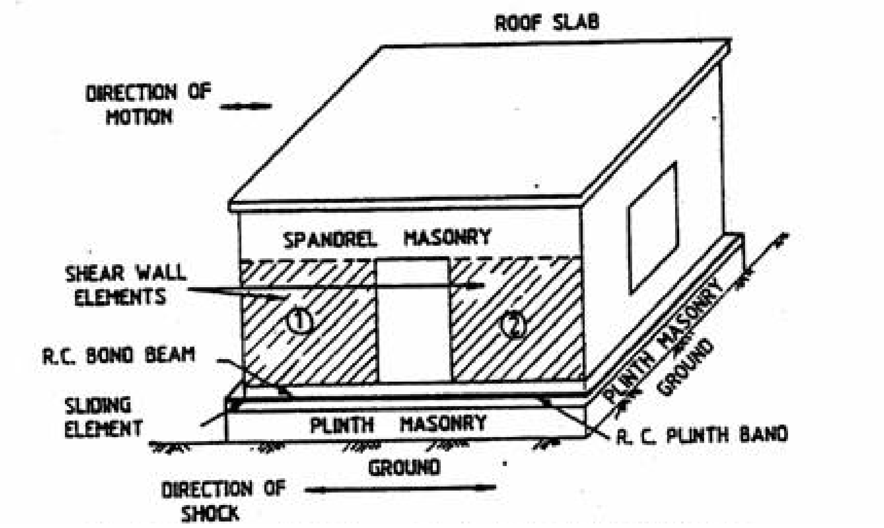


Figure 63. Idealised FSI brick house.

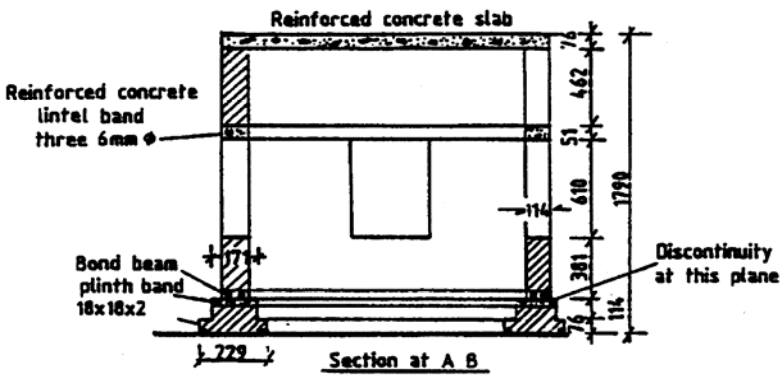


Figure 64. Brick model used for sliding base construction.

A.7 Other isolation systems

[18] H Ahmadi, K Fuller and I Goodchild. 2004. 'Novel Devices for the Isolation of Floors Against Earthquakes and Ambient Vibrations'. *13th World Conference on Earthquake Engineering, Vancouver BC, Canada (Paper No. 2216).*

The author proposed using a commercially available air-spring of diameter 600 mm to act as a belt on a fabric bag filled with liquid and air. A schematic view of the device section is shown in Figure 65. After extensive preliminary testing, the percentage of liquid for a final prototype device was chosen. A detailed test programme on this device was then carried out. Results were stated to be satisfactory. However, this system is not robust and is unlikely to be acceptable in New Zealand.

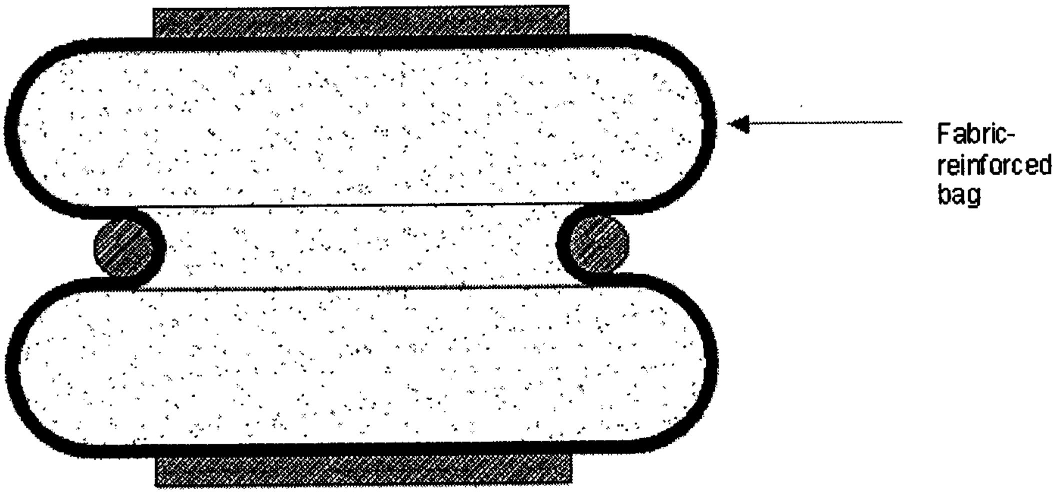


Figure 65. Section through 2D isolator.

[19] S Ishimaru, I Hata, Y Shimomura, Y Ikeda, H Ishigaki and Y Ogushi. 2004. *13th World Conference on Earthquake Engineering, Vancouver BC, Canada (Paper No. 2204).*

This was a feasibility study of new type seismic isolation – composed of piles within pipes and dampers with partial soil improvement. The concept (Figure 66) is similar to that used in New Zealand for the Wellington Central Police Station. The authors' system consisted of inner core piles founded on a bearing stratum (approximately 6 m depth) and an outer core. The piles are intended to be soil improvement columns. An outer pile allows pile-free movement and is only 2 m long. Viscous and elastoplastic dampers are used between the inner core piles and the foundation.

This is an expensive system and not applicable to the current project.

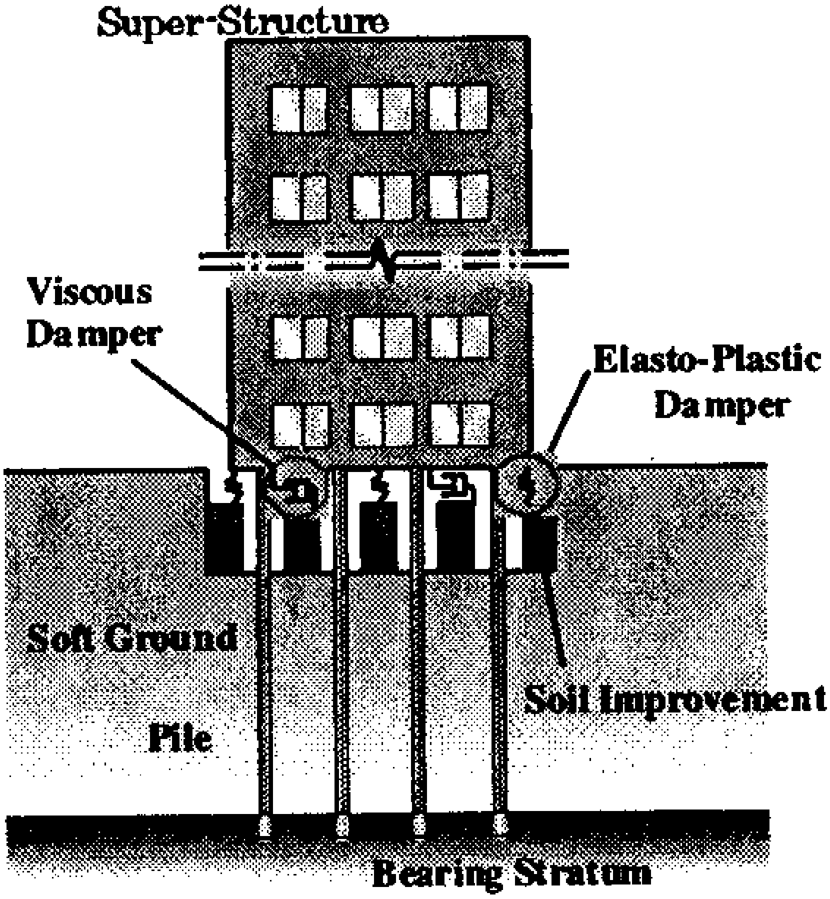


Figure 66. Concept.

[20] O Leif, I Nielsen, H Mualla and I Yuuichi. 2004. 'Seismic Isolation With a New Friction-Viscoelastic Damping System'. *13th World Conference on Earthquake Engineering, Vancouver BC, Canada (Paper No. 249).*

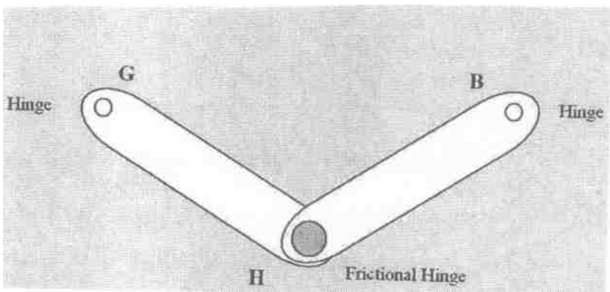


Figure 67. Friction damper.

The device shown in Figure 67 has been installed in a new RC five storey building in Japan.

The friction damper (FD), as shown in Figure 67, consists of two rigid plates (HG and HB) connected in the rotational hinge H. The moment-rotation behaviour in H is elastic-frictional. When the damper is used for base isolation of a structure, the two plate end points (connection points) are moment-free connected to ground (G) and structural base (B). When the distance between the connection points changes, so too does the angle between the damper plates. The damper dissipates energy when the elastic rotation limit is exceeded i.e. if sliding occurs in the hinge.

The use in a building is shown in Figure 68. Although this device was stated to be low cost, it is expected to be too expensive for the goals of this BRANZ project. Special details are required at column ends to carry the axial load to the ground.

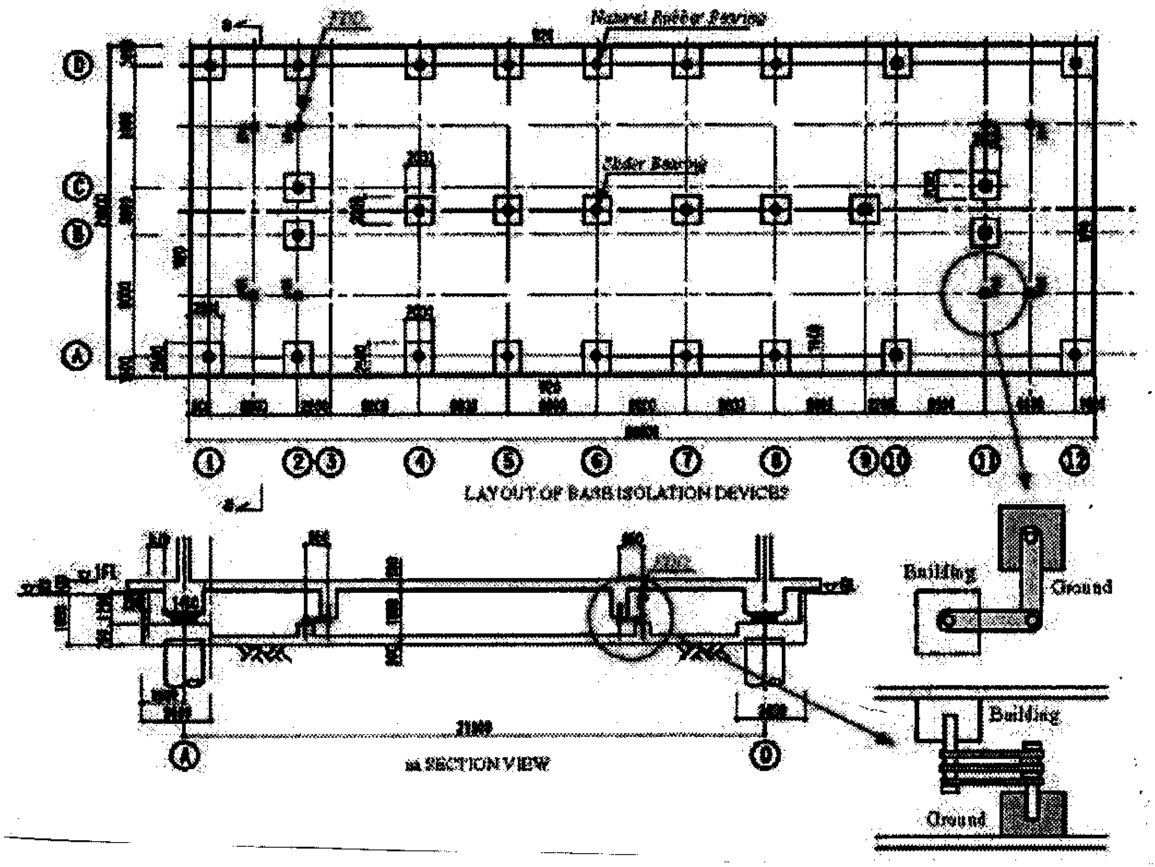


Figure 68. Layout of damper locations at base of building.

[21] T Hanai, S Nakata, S Kiryama, and N Fukuwa. 2004. 'Comparison of Seismic Performance of Base-Isolated House With Various Devices'. *13th World Conference on Earthquake Engineering, Vancouver BC, Canada (Paper No. 1203).*

The authors tested various types of BIDs under a two storey building on a shake table, including ball-bearing and slide type devices suitable for light structures.

The response properties of three types of BIDs were compared under identical conditions by conducting shaking table tests in which a single house superstructure was used in combination with different types of BIDs. All of the devices tested proved to be effective so that for the input ground motions used in the test, the response acceleration was significantly lower than the input acceleration. No interior or exterior damage was found in the superstructure and bookcases placed in the structure did not topple over.

However, comparisons were not made with a non-base-isolated house.

[22] S Kawamata, N Funaki, N Hori, T Fujita and N Inoue. 2004. 'Base Isolation System Suitable for Masonry Houses'. *13th World Conference on Earthquake Engineering, Vancouver BC, Canada (Paper No. 668).*

The authors proposed base-isolating houses by using rocking pillars to support a superstructure (Figure 69 to Figure 71). The pillar is from a steel tube filled with concrete with spherical caps. A damper between the pillars and caisson is required to limit movement and provide restraint to wind movement. The authors constructed a specimen on a shake table and were able to accurately predict its natural frequency without dampers. The natural period with dampers was rather low for a base-isolated structure (0.63 s) and indicated limited isolation. However, the authors reported more than 80% reduction in acceleration. It is doubtful whether the displacement across the isolator was only 7 mm.

Although this system has potential as bridge piers, it is expected this type of construction to be expensive in practice and to be beset by practical problems. Waterproofing the system would also be a problem.

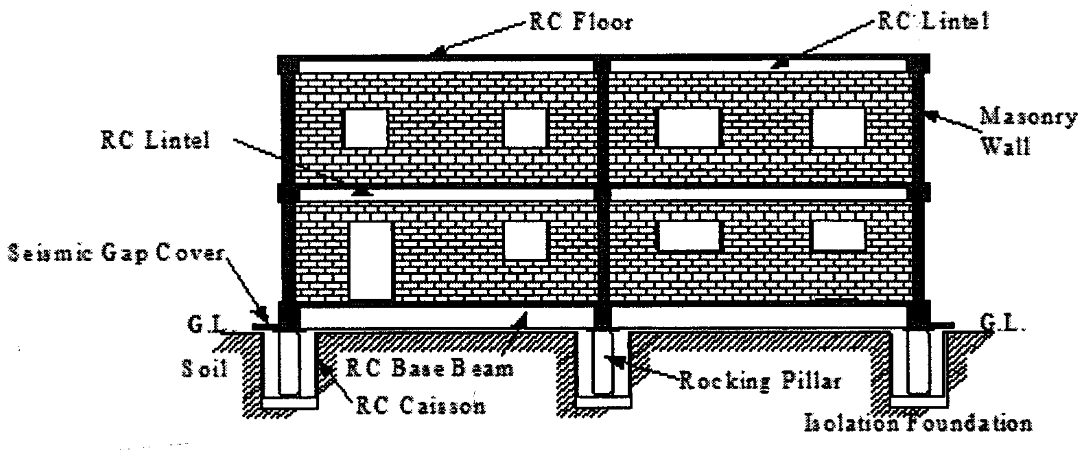


Figure 69. Expected typical use of rocking pillar system.

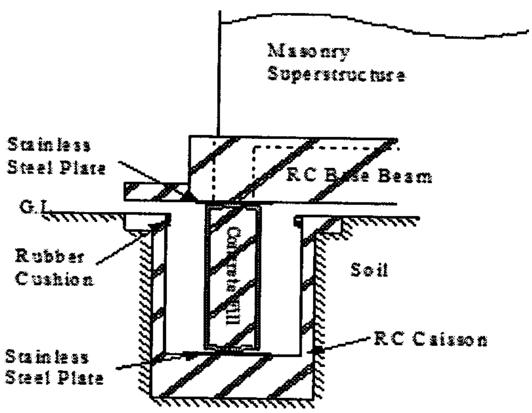


Figure 70. Scheme of isolation foundation.

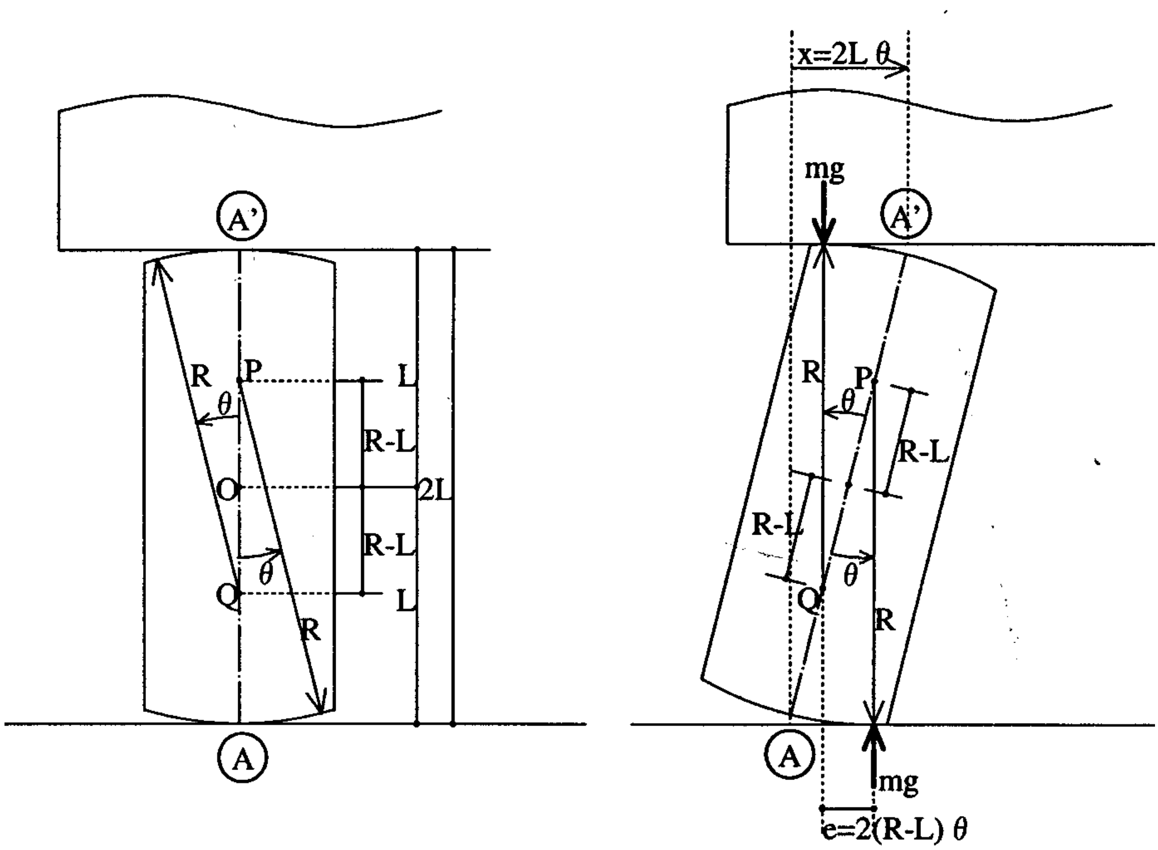


Figure 71. Movement of rocking pillar.

[23] RS Jangid and YB Lonahe. 1998. 'Effectiveness of Elliptical Rolling Rods for Base Isolation'. *Journal of Structural Engineering* 124 (24).

The concept is similar to a building founded on spherical roller bearings, except that the shape of the bearings is elliptical. Under lateral displacement, this imposes a restoring force so that the building is almost centred after the earthquake and reduces the total displacement. However, if a critical displacement is exceeded the motion becomes centred about a new origin, and thus the rods must have a big 'large' radius. The authors used 200 mm in their example.

As the effective friction coefficient is very low (approximately 0.01), the building will be susceptible to wind-induced motion unless other types of lateral resistance are provided.

[24] V Briman and Y Ribakov. 2006. 'Seismic Isolation Columns for Earthquake Resistant Structures'. *Proceedings of the 8th US National Conference on Earthquake Engineering, 2006, San Francisco, California, USA (Paper No. 792).*

This paper dealt with a new constructive solution for seismic isolation which can only be used in a structural scheme with an open ground floor. This construction is rare in New Zealand, but more common in Europe. The proposed solution is based on the idea of pendulum suspension brackets installed in seismic isolation columns. The main differences between existing solutions and the proposed one are that the latter requires no additional space for its installation, its lifetime corresponds to that of the structure, and no maintenance is required during the entire period. The proposed solution provides additional damping and, like other base-isolation systems, shifts the vibration period of the structure, reducing its spectral response. Since its size is compact, the ground floor columns of existing structures with low seismic capacity may be replaced by the proposed ones. It yields significant improvement in structural seismic response. Numerical simulation shows that buildings where the proposed system is installed are likely to sustain minimal damage or none at all, whereas traditionally designed ones may suffer major damage or even collapse due to the same earthquake.

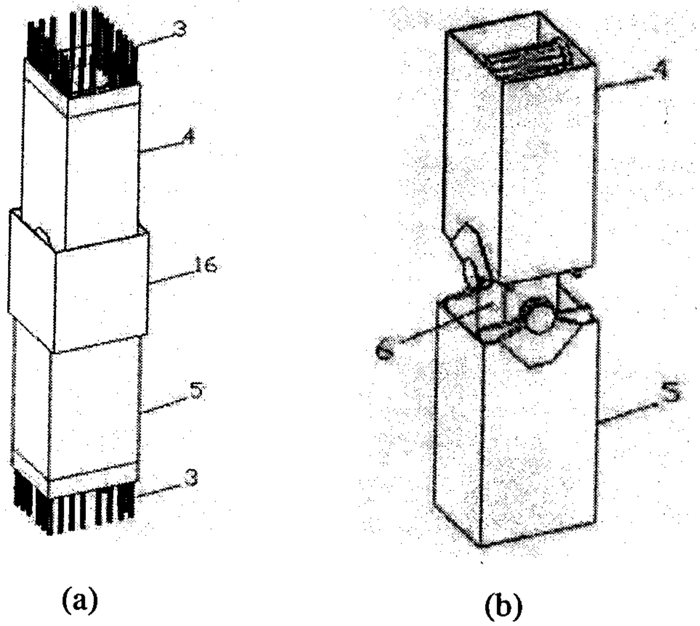


Figure 72. A view of a SIC (a) with covering and connection elements, (b) without covering.

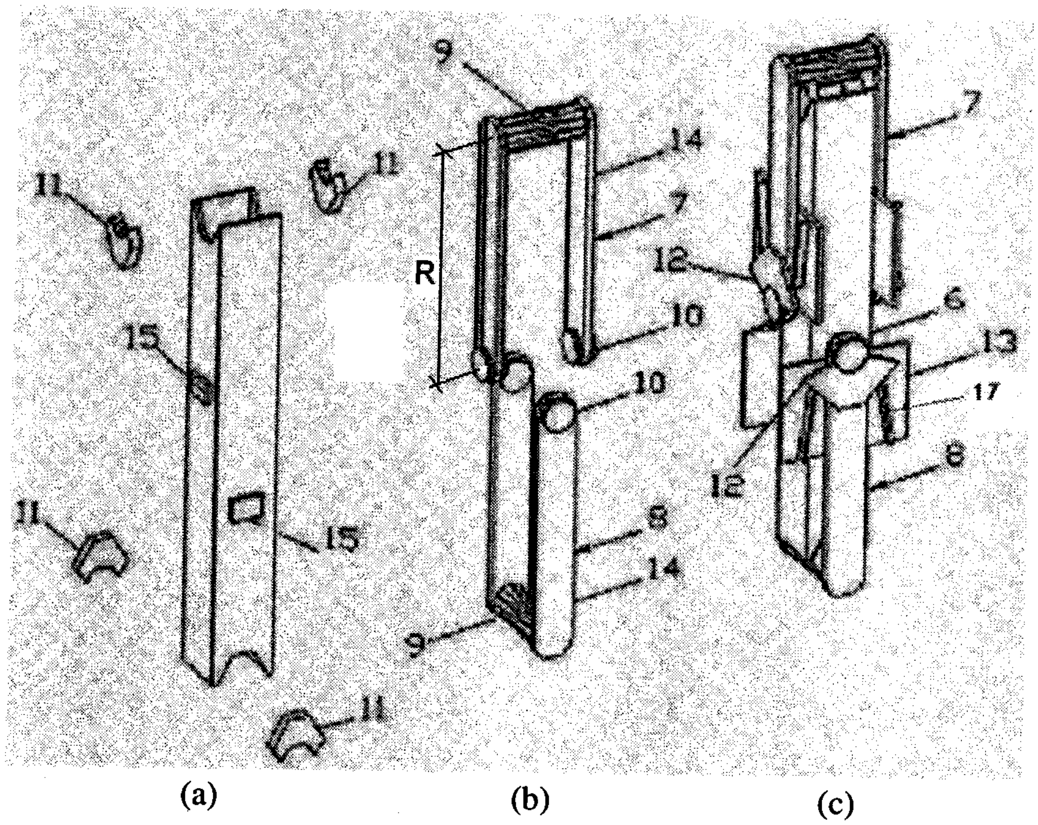


Figure 73. Inside SIC details (a) inside column, (b) pendular suspension bracket, (c) inside column with rigidly connected elements.

[25] T Kanakubo, A Yasojima and T Furuta. 2004. 'Earthquake and Wind Response of Base-Isolated Wooden Houses Using MR Dampers'. *13th World Conference on Earthquake Engineering, Vancouver BC, Canada, 1-6 August 2004 (Paper No. 619).*

Developments of lock system for base-isolated wooden houses were conducted using Magneto-rheological fluid dampers (MR dampers). The damping force of an MR damper was changed by a simple mechanism.

Dynamic vibration tests of an MR damper were carried out to investigate the mechanical properties and adaptability. Load versus displacement curves of an MR damper were represented by a velocity powered model, and parameters of the model were obtained from test results. Using this model, earthquake and wind response analysis was carried out for a two storey base-isolated wooden house. The lock system of the MR damper was controlled so that the isolated layer was locked until the force from a 45m/s wind velocity was reached. For earthquake motion, analysed responses for the building using MR dampers showed almost identical response to the building using ordinary viscosity dampers. Under wind, it was 50% as effective as using ordinary viscosity dampers.

A sketch of the lock system using MR dampers is shown in Figure 74. Usually the MR damper is locked by a magnetic field. Input energy of a strong wind is absorbed and only a small displacement of the MR damper occurs. However, in an earthquake the permanent magnets fall down at a target acceleration which makes the MR damper behave as an ordinary oil damper.

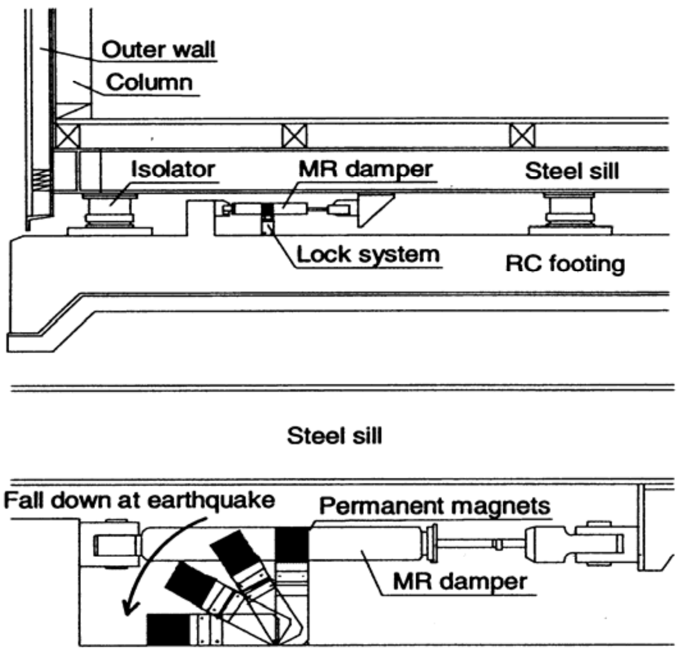


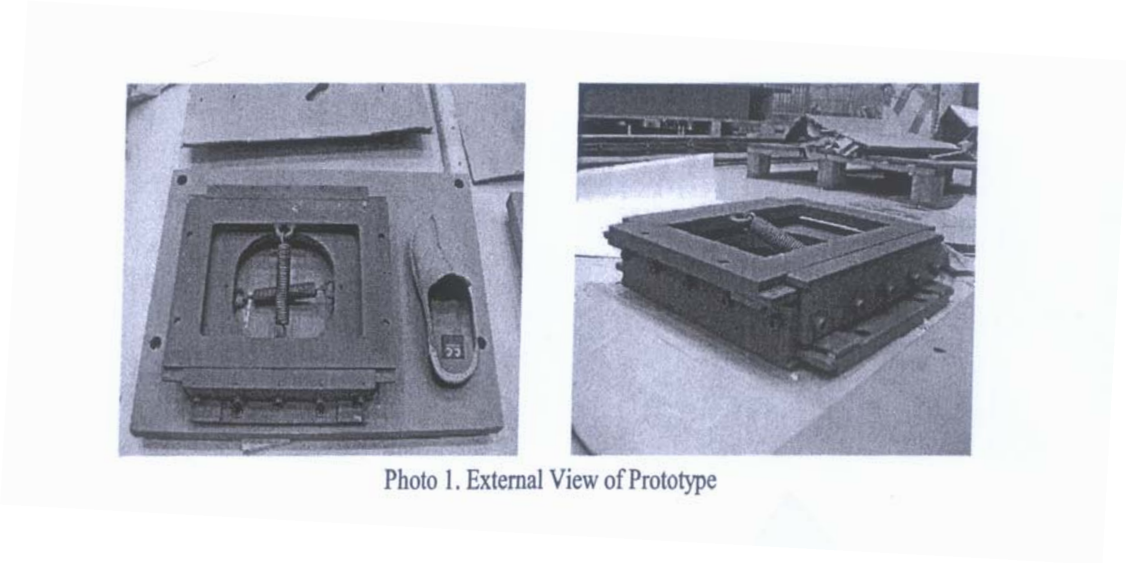
Figure 74. Dynamic vibration test of an MR damper.

[26] T Uematsu, Y Ishiyama, Y Aoki, H Kuramochi, T Kojima, T Sogo, H Nakayama, E Kobayashi, Y Nishino and M Miyagi. 2004. 'Development of Compact Vibration Isolation Equipment Applicable to Existing Residences – Restoring Mechanism Utilizing Roller Bearings'. *13th World Conference on Earthquake Engineering, Vancouver BC, Canada, 1-6 August 2004 (Paper No. 387).*

The authors describe a device (patent pending) that can be easily installed without heavy construction equipment or special skills. There is a cylinder shaped roller and an oil version available. The devices can move ±200 mm and carry a load of 5 tonnes.

The effective friction coefficient was 0.0035 for the oil device, but was not stated for the roller device.

The authors' shake table test found bottles filled with water did not fall in tests using the isolated structure (although they never stated they did in the unisolated structure). This may have been due to the extremely low coefficient of friction of the devices.



[27] A Iqbal. 2006. **'**Friction Pendulum System in Seismic Isolation: Research, Testing and Applications'. *Proceedings of the 8th US National Conference on Earthquake Engineering, 18-22 April 2006, San Francisco, California, USA (Paper No. 1760).*

The author discusses construction projects which have used the Friction Pendulum System (FPS) shown in Figure 75, and the various scaled and full-scale shake table tests performed.

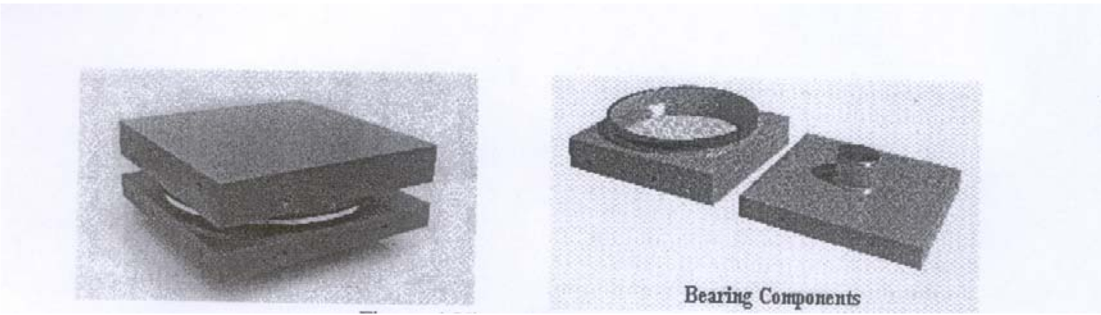


Figure 75. View of FPS bearings.

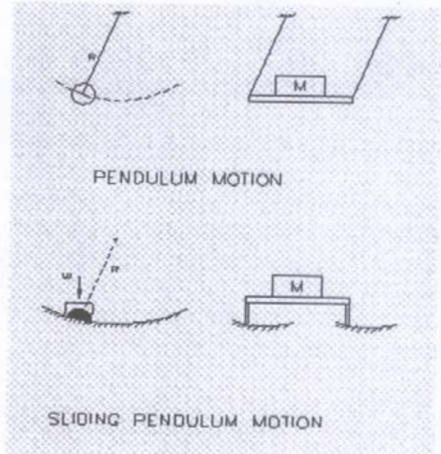


Figure 76. Basic principles of FPS bearings.

[28] NJ Gakkai. 1990. *Toraiborojisuto Journal of Japanese Society of Tribologists* (in Japanese).

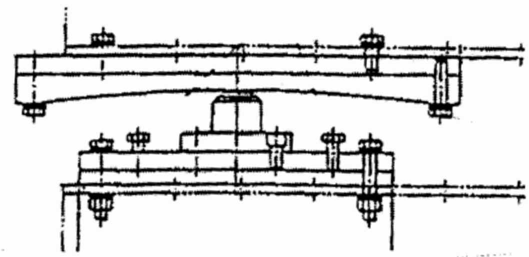


Figure 77. Proposed base-isolation scheme using a conical bearing surface.

This paper was in Japanese which could not be read. However, the device shown in Figure 77 has merit and it provides both a sliding isolator with an increasing resistance with deflection.

[29] PC Roussis and MC Constantinou. 2006. **'**Seismic Response Analysis of Structures Equipped With Uplift-Restraining Sliding Isolation Bearings: A Case Study'. *Proceedings of the 8th US National Conference on Earthquake Engineering, 2006, California, USA (Paper No. 1599).*

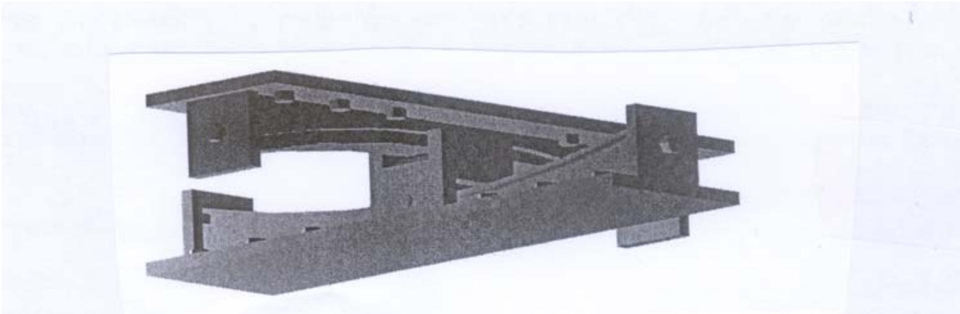


Figure 78. XY-FP base-isolation system.

Based on the Friction Pendulum (FP) principle, the XY-FP isolation bearing consists of two orthogonal concave beams interconnected through a sliding mechanism that permits tensile forces to develop in the bearing, thus preventing potential uplift (Figure 78).

A.8 Conventional rubber bearings

[30] JM Kelly. 2006. *Base Isolation: Origins and Development.* Paper from website http://nisea.berkeley.edu/lessons/kelly.html. University of California, Berkeley, USA.

An extensive series of tests on the five storey frame demonstrated that isolation with rubber bearings could provide very substantial reductions in the accelerations experienced by both the building and internal equipment. However, the same tests showed that when additional elements (such as steel energy-absorbing devices, frictional systems, or lead plugs in the bearings) were added to the isolation system to increase damping, the reductions in acceleration to the equipment were not achieved because the added elements also induced responses in the higher modes of the structure, affecting the equipment. The optimum method of increasing damping was to provide it in the rubber compound itself. This was subsequently applied in the first base-isolated building in the United States.

[31] HR Ahmadi, KNG Fuller and AH Muhr. 1995. 'Design and Performance of High Damping Natural Rubber Base-Isolators'. *Proceedings 2nd International Conference on Seismology and Earthquake Engineering, 1995, Tehran, Islamic Republic of Iran.*

The authors describe a base-isolated building with bearing connection system shown in Figure 79. The structure is a four storey reinforced concrete frame with masonry block infill typical of low cost construction in Indonesia. It has a plan area of approximately 18 x 8 m, there being two small apartments on each floor.

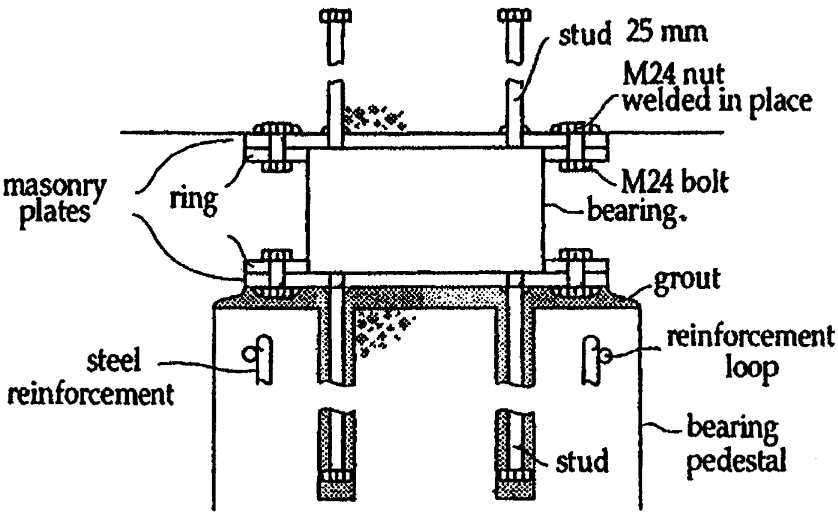


Figure 79. Bearing connection system.

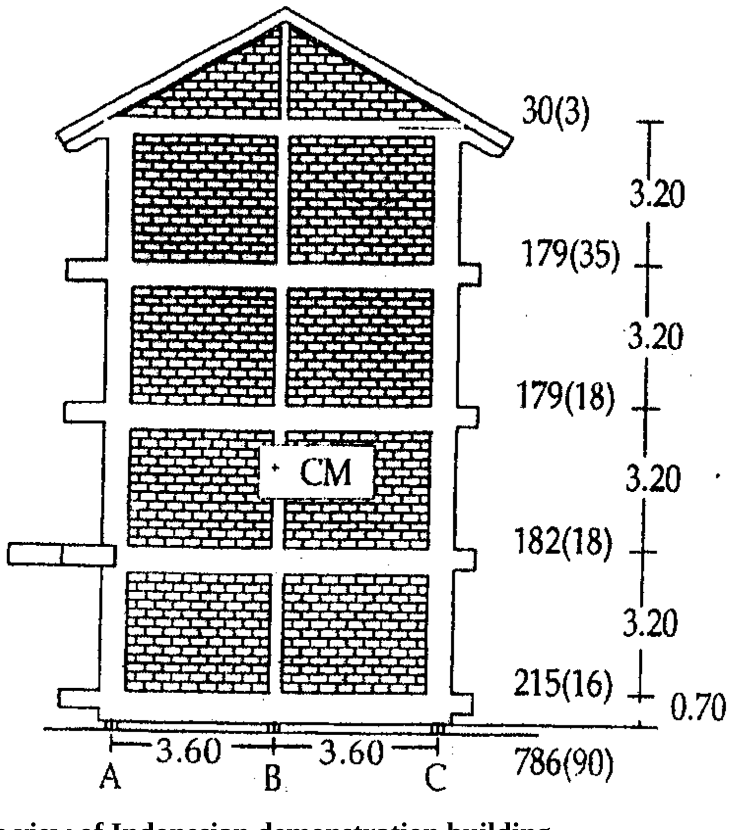


Figure 80 Side view of Indonesian demonstration building.

Dead loads (t) assigned to each level and corresponding full live loads in brackets are shown. + position of centre of mass. Dimensions (m).

[32] MJ Sarrazin. 1992. 'Design and Construction of a Building on Seismic Isolators'. *Bulletin of IISEE* 26 (1992): 481-497.

The author describes the construction of two four storey masonry buildings, identical except for the fact that one of them rests on isolators. Both buildings will be equipped with accelerators, aimed at comparing their response to a destructive earthquake.

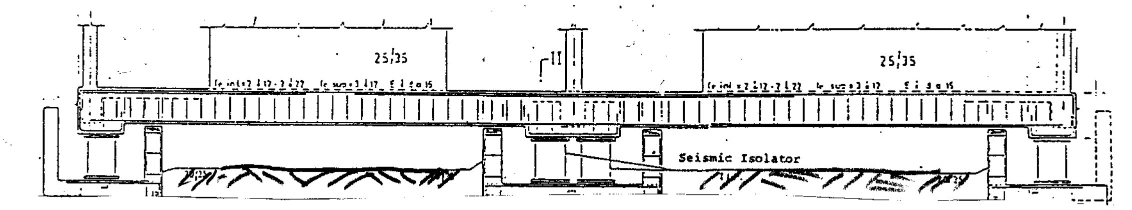


Figure 81. Isolation system.

The isolated building was mounted on eight rubber isolators, which rested on foot foundations, connected by reinforced concrete beams (see Figure 81). A small retaining wall surrounds the building and is separated from it by a 20 cm gap. Its function is to permit the isolation bearings to move during an earthquake.

The economic evaluation projected elevated costs for the incorporation of the isolators was 25% of the total cost of the construction. The additional expense was not only a result of the cost of the isolators themselves and their anchorages, but also reflected the cost of additional civil works (an additional slab, deeper foundations etc). Moreover, the reduced seismic forces affecting the isolated building were not taken into consideration for this project. The primary reason for this was the need to compare buildings with equivalent physical characteristics. However, the cost of the building was very low, being US$7,000 per apartment.

[33] W Taniwangsa and JM Kelly. 1996. 'Experimental and Analytical Studies of Base Isolation Applications for Low-Cost Housing'. *Earthquake Engineering Research Center Report No. UCB/EERC-96/04 (July 1996).*

This report describes low cost natural rubber isolation systems for public housing in Italy, Indonesia, Chile and China, with particular emphasis on the Indonesian building, including analysis and laboratory testing. A retrofitted building in America and a proposed new building in India are referred to.

The isolation in all instances was provided by rubber bearings using either bolted connections or shear key connections. The structures were RC frame (with bearings below column stubs), reinforced concrete walls, confined masonry or RC frame with masonry infill. They varied in height from three to eight storeys.

It was noted that for small buildings where columns are lightly loaded, bearings using typical rubber would need to have a small diameter and total thickness to provide the required seismic properties. However, this leads to an unstable bearing design. To overcome this, carbon black was added to the rubber to decrease the lateral stiffness.

[34] W Taniwangsa, PW Clark and JM Kelly. 1996. 'Natural Rubber Isolation Systems for Earthquake Protection of Low-Cost Buildings'. *Earthquake Engineering Research Center Report No. UCB/EERC-95/12 (June 1996).*

This report describes the testing and properties of bearings used in low cost public housing projects in Indonesia and China.

<u>Modified rubber bearings</u>

[35] JM Kelly. 2002. 'Seismic Isolation Systems for Developing Countries'. *Earthquake Spectra* 18 (3).

Kelly proposed replacing the intermediate steel plates of a conventional rubber bearing with mats of carbon fibre. These could be manufactured in long strips and then cut to appropriate lengths. When used under structural walls, beams are needed to carry the wall from isolator to isolator. Kelly developed a theory for calculating the vertical stiffness to take into account the matt flexibility. This was largely confirmed by experimental testing.

[36] T Alexander. 2004. *The Use of Recycled Rubber for Base Isolation of Structures.* University of California, Berkeley, USA, C.E. 290D. Research project supervised by Professor J Kelly.

This paper examines the possibility of using recycled tyre rubber in base isolation, in particular the process through which crumb rubber is created and the processes through which it is remade into rubber parts. Use of whole tyres for isolation of structures was also considered, particularly when filled with sand and used as a buffer to limit seismic movement. Recycled rubber could lower the cost of manufacturing isolation bearings without changing the process much or decreasing bearing performance by more than 50%. Recycling also helps the environment, uses discarded tyres, and can help earn tax credits for building projects.

[37] JM Kelly and SM Takhirov. 2001. 'Analytical and Experimental Study of Fiber-Reinforced Elastomeric Isolators'. *PEER Report 2001/11.* Pacific Earthquake Engineering Research Center, University of California, Berkeley, USA, September 2001.

The authors described theoretical and experimental analyses to determine the mechanical characteristics of multi-layer elastomeric isolation bearings where the reinforcing elements, normally steel plates, are replaced by a fibre reinforcement. The fibre-reinforced isolator, in contrast to the steel-reinforced isolator (which is assumed to be rigid both in extension and flexure), was assumed to be flexible in extension, but completely without flexure rigidity.

The influence of fibre flexibility on the mechanical properties of the fibre-reinforced isolator, such as the vertical and horizontal stiffness, was studied and shown to produce a fibre-reinforced isolator that matches the behaviour of a steel-reinforced isolator. The fibre-reinforced isolator will be significantly lighter and could lead to a much less labour-intensive manufacturing process.

[38] GC Delfosse. 1982. **'**Wood Framed Individual Houses on Seismic Isolators'. *Proceedings of the International Conference on Natural Rubber for Earthquake Protection of Buildings and Vibration Isolation.*

The paper explains why base isolation for light-weight buildings is difficult to design, as their low mass requires low stiffness rubber bearings which thereby can become unstable under lateral load due to P-delta effect. The paper proposes solutions.

APPENDIX B. INFORMATION ON NEW ZEALAND MASONRY BUILDINGS

Alistair Allan of Firth Industries kindly responded to my questions regarding use of masonry buildings in New Zealand. An extract from our communication is given below with permission from Mr Allan.

1. **Question:** Do most masonry buildings have few problems in providing sufficient bracing rating to meet code seismic demand loading or is it often a significant issue? (If it is not an issue then the only justification for base isolation is protection of building contents in an earthquake.)

   Answer. Generally there is enough masonry wall length available to provide the required bracing – it is simply a matter of working out how much reinforcing is required in the relevant wall panels. From time-to-time, portal frames are added to supplement the available masonry – this would occur in less than 5% of buildings.

2. **Question:** What floor system do you use for your suspended floors?

   Answer: We recommend that suspended floors be constructed in concrete using 'Unispan' or 'Interspan'. The choice will depend on spans and aesthetic requirements for the ceiling to the space below.

3. **Question:** Do most two storey masonry buildings have masonry at both levels or does the second storey often have a light-weight cladding?

   Answer: Generally we would view a masonry building as being built with solid masonry to all floors. A house with light timber frame and brick or other cladding to the top storey and a masonry lower floor is normally characterised by the upper floor construction, with the rider that it is "built on a block base".

4. **Question:** Do most new masonry buildings use the 'hot blocks'?

   Answer: Almost all masonry homes using Firth product are built in HotBloc™. It is normally conservatively assumed that HotBloc™ weighs the same as a standard block of the same size.

Comment: To date, solid masonry has typically been used for more 'upmarket' homes. The result is that they are normally architecturally designed', and so tend to be widely varying in their shape and size. Greater than two storeys would only apply to less than 5% of buildings and normally only arises on difficult sites – e.g. steep grades.