STUDY REPORT

No. SR 177 (2007)

Base Isolation of Low-rise Buildings Using Synthetic Liners

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Preface

This is the second Study Report prepared during research into base isolation of low-rise buildings. There were also four BRANZ unpublished reports on this subject. However, the key findings from these unpublished reports were reproduced in the first study report SR 156 'Base Isolation of Low-rise Light and Medium-weight Buildings'.

Acknowledgments

This work was funded by the Foundation for Research, Science and Technology from the Public Good Science Fund.

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 BUILDINGS USING SYNTHETIC LINERS

BRANZ Study Report SR 177 (2007) **SJ Thurston**

Reference

Thurston SJ. 2007. 'Base Isolation of Low-rise Buildings Using Synthetic Liners'. BRANZ *Study Report SR 177(2007)*. BRANZ Ltd, Judgeford, New Zealand.

Abstract

This report presents the results of a preliminary investigation into the practicality of base isolating low-rise buildings by placing synthetic liners beneath the foundation slab. The slip coefficients as a function of axial load, number of cycles and velocity were determined for various liners with both standard and modified surfaces. The effects of grit on the surface and lap joints between sheets were examined.

Keywords

Base isolation, isolation, synthetic liners, seismic protection, earthquake protection, low-rise buildings, timber-framed houses.

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1. INTRODUCTION

This document has been prepared to meet the BRANZ year 2006–2007 revised contract with GNS to meet Objective 2 (New Applications of Seismic Isolation) in PGSF contract number C05X0301 with GNS. Background to the work is discussed by Thurston (2006). Four BRANZ unpublished reports under this topic are summarised by Thurston.

Other parties to this contract are GNS and Robinson Seismic Ltd. Robinson Seismic Ltd continues developing the Roball™ and Roglider™ base-isolation devices.

2. LITERATURE REVIEW

Many authors have advocated using a slip layer beneath a building slab foundation to provide base isolation. Major works are discussed below.

Building services, particularly water and sewerage, which cross a slip surface are likely to rupture. A possible solution is to coil such services in a sump to the side of the building and allow them to enter the building above the slip layer. Provision of services is an important aspect which needs to be fully addressed before the solutions advocated below can be used.

Paper 1

Yegian and Kadakal (2004) proposed placing smooth synthetic materials beneath building foundations as shown in Figure 1 to provide a slip layer. Based on shake table tests, they concluded that Typar 3601 geo-textile placed over an ultra-high molecular weight polyethylene (UHMWPE) was most suitable. They measured 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 using a layer of site concrete, then two sliding synthetic layers followed by a base concrete slab (see Figure 1). The writer notes that 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.

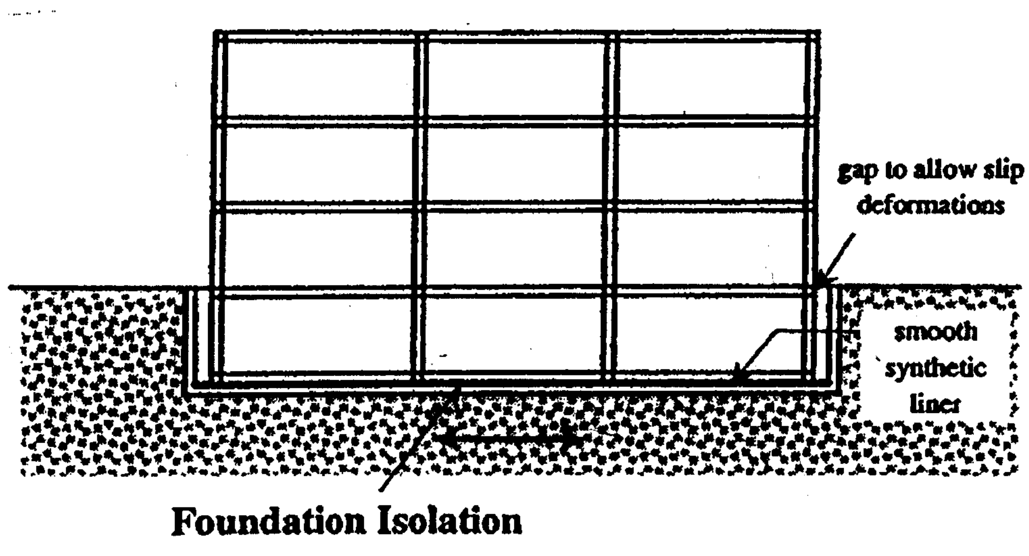
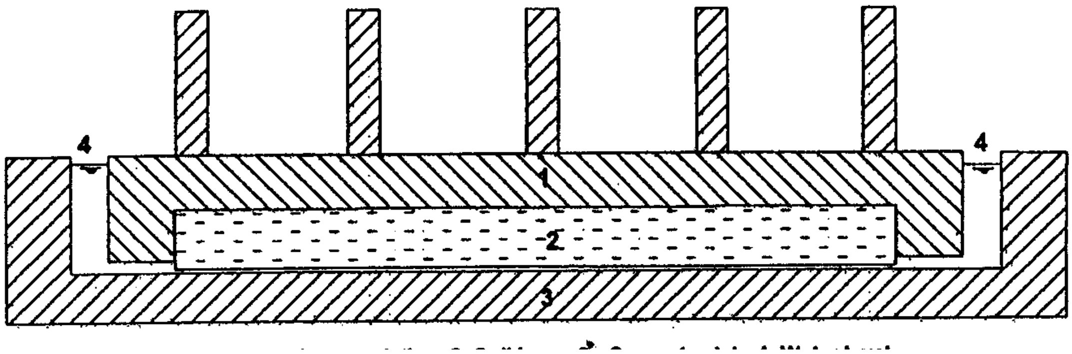


Figure 1. Foundation isolation for seismic protection of buildings using smooth synthetic liner

Paper 2
Doudoumis et al (2002) propose placing soil layers with low shearing resistance beneath buildings. This 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, were investigated by analytical study.

The authors proposed the system shown in Figure 2 to avoid lateral passive reaction of the surrounding soil.



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

Figure 2. The basic concept of interposing an artificial soil layer

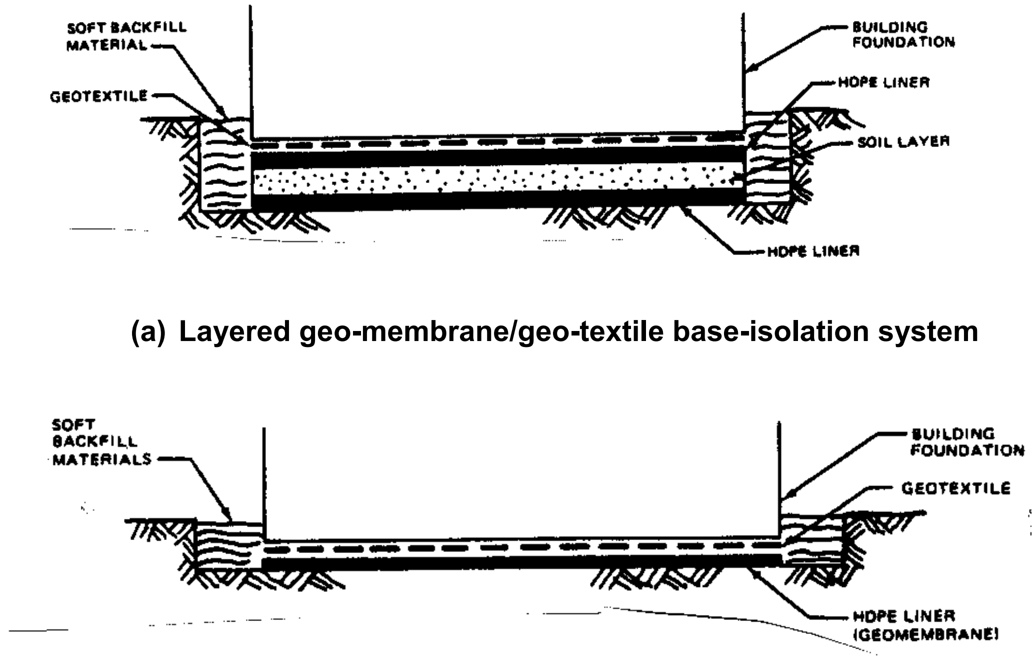
The authors suggested that low shearing resistance of the interposed artificial soil layer can be provided by suitable natural materials, for example, granular products of rocks containing low friction minerals (talc, chlorite, serpentine etc), or high plasticity clays (such as montmorillonitic clays). Selected granular rock products can meet the requirements of a low friction with relatively low shearing resistance and an adequate 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 2).

However, the writer considers that the construction shown in Figure 2 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 authors 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.

Paper 3
Based on shake table tests, Kevazanjian et al (1991) found the system in Figure 3(a) provided good base isolation. In the single layer synthetic-liner (SLS-L) system of Figure 3(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 3(a).

Measured static coefficients of friction varied between 0.12 to 0.22 g while the 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 used.

The writer notes that 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.



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

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

Figure 3. Application of synthetic liner base isolation

Paper 4

Xiao et al (2004) also proposed using a low friction layer beneath the foundation to act as a base-isolation layer – but stated that this was only for heavy buildings made from weak building materials. The proposed construction method is shown in Figure 4. Suggested isolation materials with corresponding measured friction levels are given in Table 1. A polythene membrane must be used beneath pebbles.

The thickness of the floor slab shown in Figure 4 is large and therefore expensive. The writer considers that if this isolation was 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.

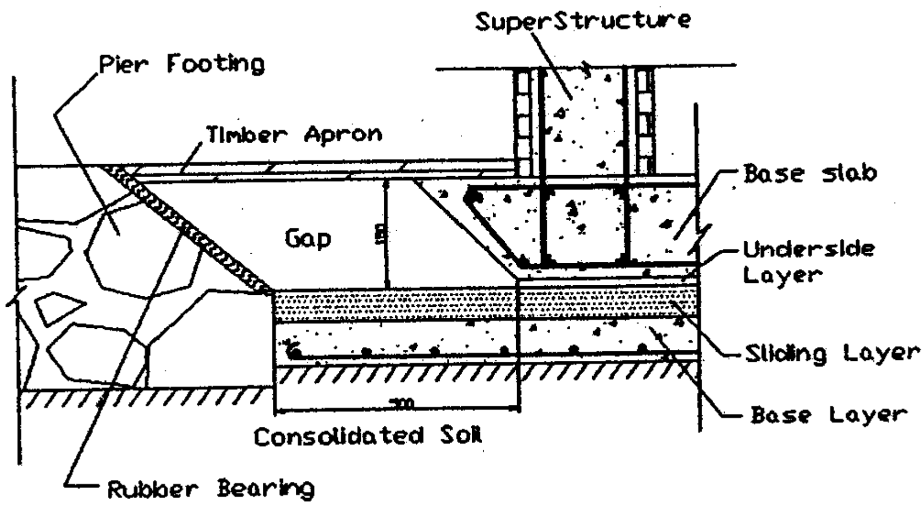


Figure 4. Proposed construction method

Table 1. Isolation level

Material	Friction coefficient
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

Paper 5

Yegian and Lahlaf (1992) performed shake table tests as per Figure 5 to measure the dynamic interface properties between a geo-membrane and geo-textile. The static coefficient of friction was found using slope tests as per Figure 6.

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

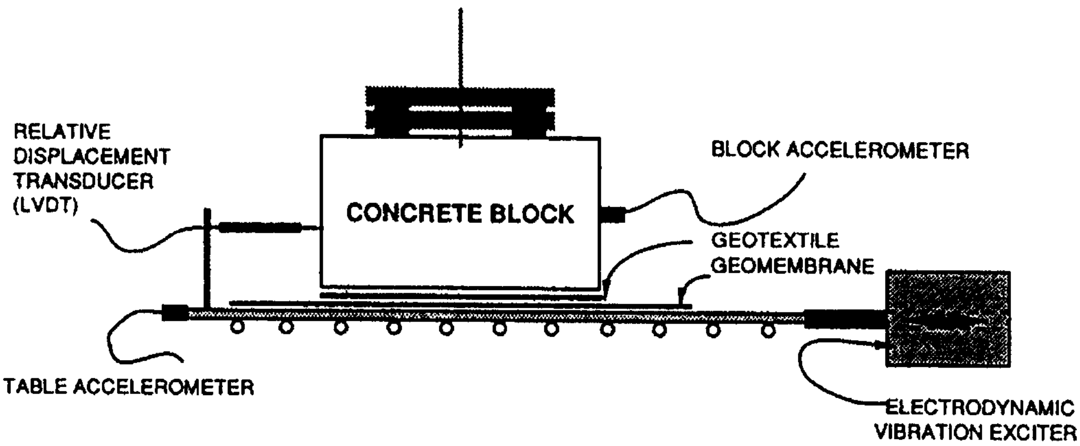


Figure 5. Shaking table facility

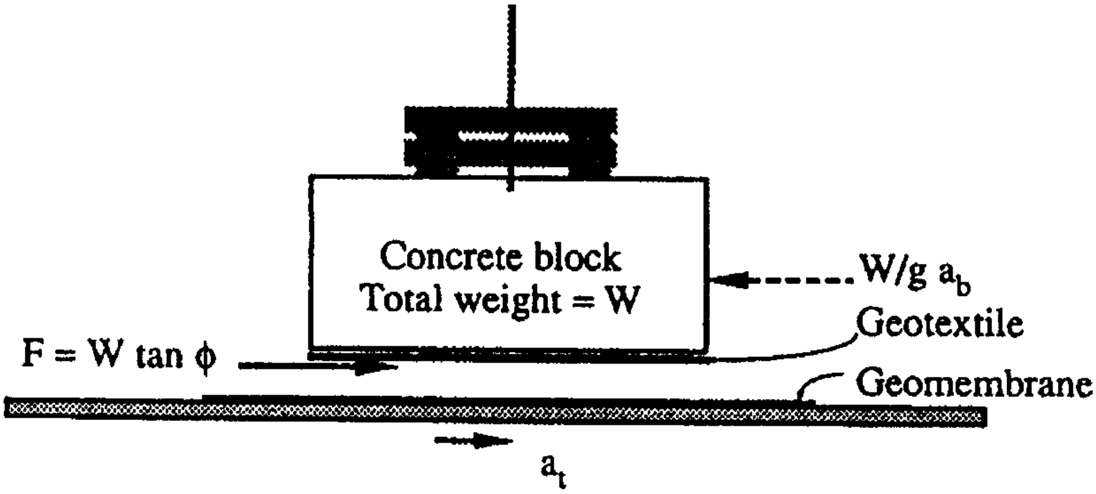


Figure 6. Free-body diagram of block

Paper 6

Yegian and Catan (2004) proposed using the same synthetic liners as Paper 1, but placed within a soil profile to dissipate seismic energy transmitted to the overlying soil layer and structure (Figure 7). This 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 8). 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 significantly reduce the peak and spectral accelerations (see Figure 9). 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 10. (H = horizontal dimension of isolated soil and D = depth to liner.)

The writer considers that that rainwater captured between the building edge and liner edge is confined and cannot drain freely and would create problems. The thickened bottom slab edges at building edges and waterproofing at this point needs careful consideration.

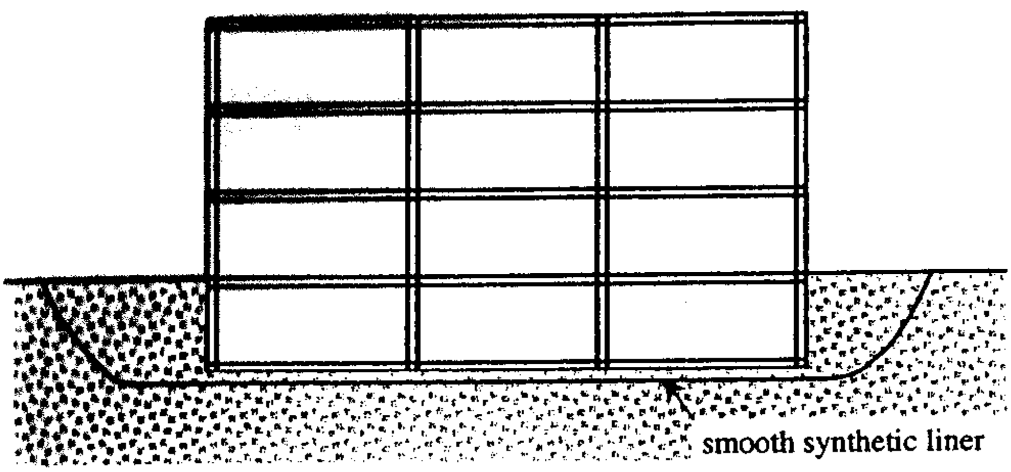


Figure 7. Soil isolation for buildings

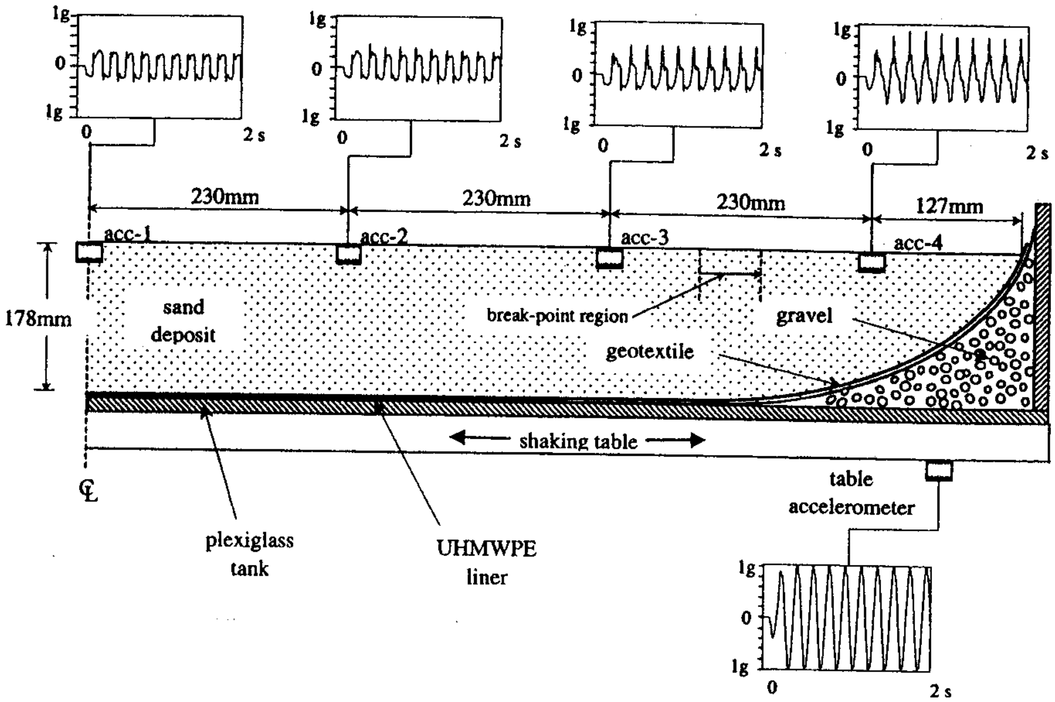


Figure 8. Acceleration records from shaking table tests on tub-shaped isolated soil subjected to a 5 Hz harmonic motion

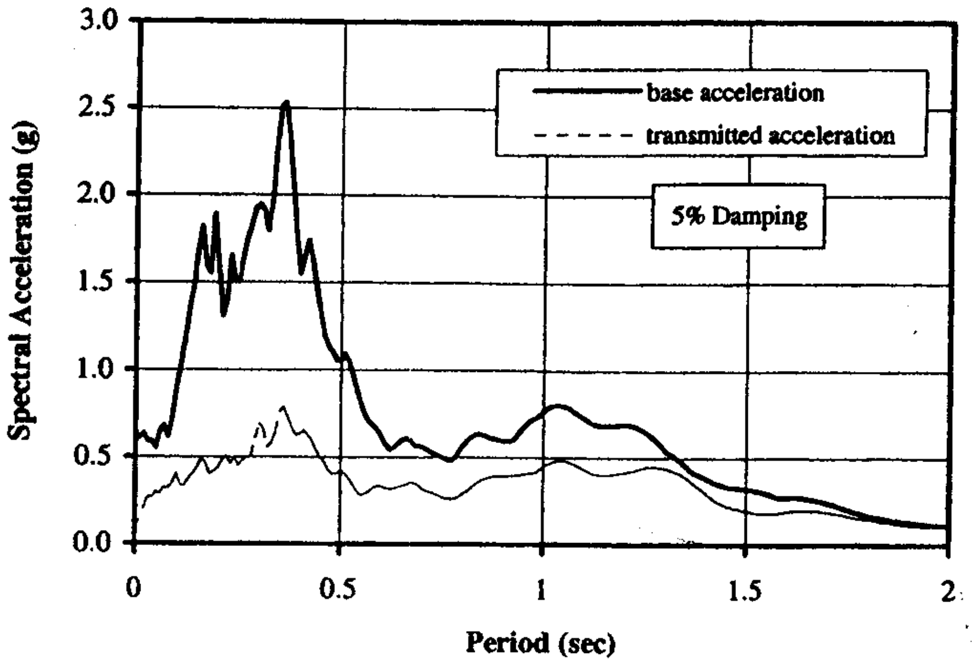


Figure 9. Transmitted acceleration response spectra of cylindrical-shaped isolated soil

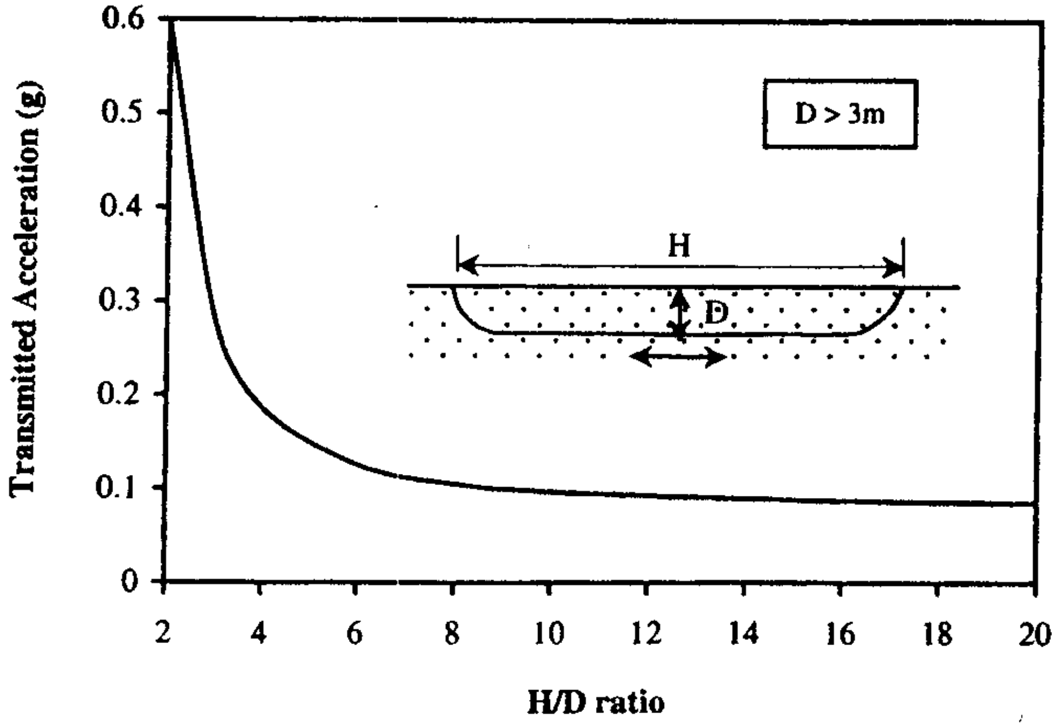


Figure 10. Transmitted acceleration as a function of H/D ratio computed analytically

3. POTENTIAL BASE-ISOLATION SOLUTIONS FOR LOW-RISE BUILDINGS

The writer used the principles given by Yegian and Catan (2004) (Paper 6) to propose a base-isolation system for typical New Zealand houses given in Figure 11. The path slides on its own slip layer but need not extend around the entire building. Steps and other obstacles must be designed to slide. The depth of the edge footing allows for edge bearing and the design has little susceptibility to water ingress. It is more likely to be practical in a sand environment when sand replacement and compaction is required anyway.

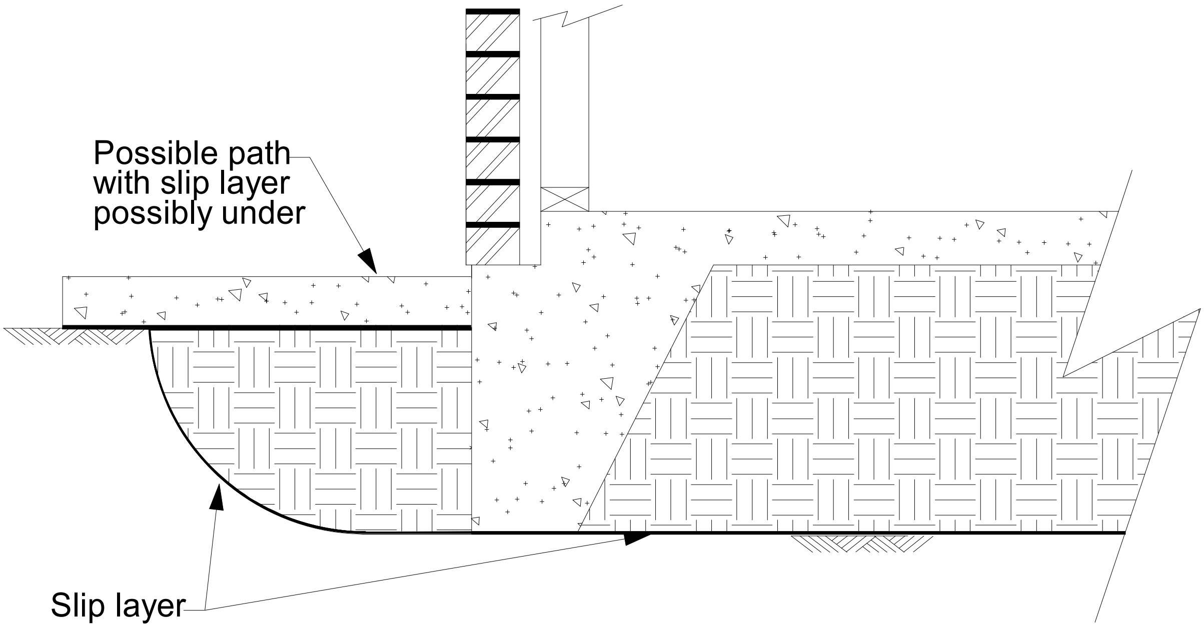


Figure 11. Variation of the system proposed by Yegian and Catan (2004)

The writer used the principles given by both Yegian and Kadakal (2004) (Paper 1) and Yegian and Catan (2004) (Paper 6) to propose a base-isolation system for standard houses given in Figure 12. The slip layer is horizontal but soil is placed above the slip layer under most of the house. A sacrificial block is used to protect the edge slip layers adjacent to the building external edges. A variation of this for a constant thickness foundation slab is shown in Figure 13.

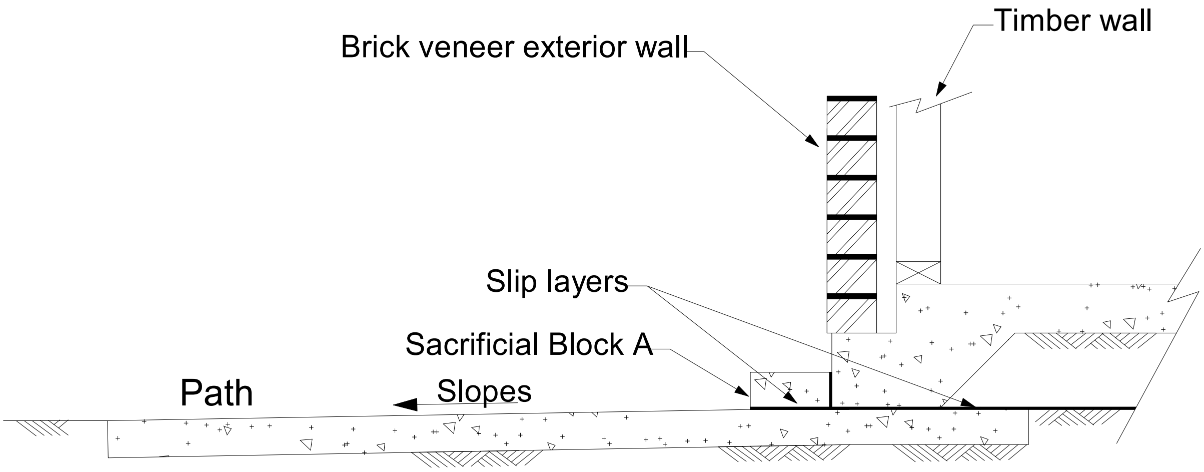


Figure 12. Variation of the systems proposed by Yegian and Kadakal (2004) and also Yegian and Catan (2004)

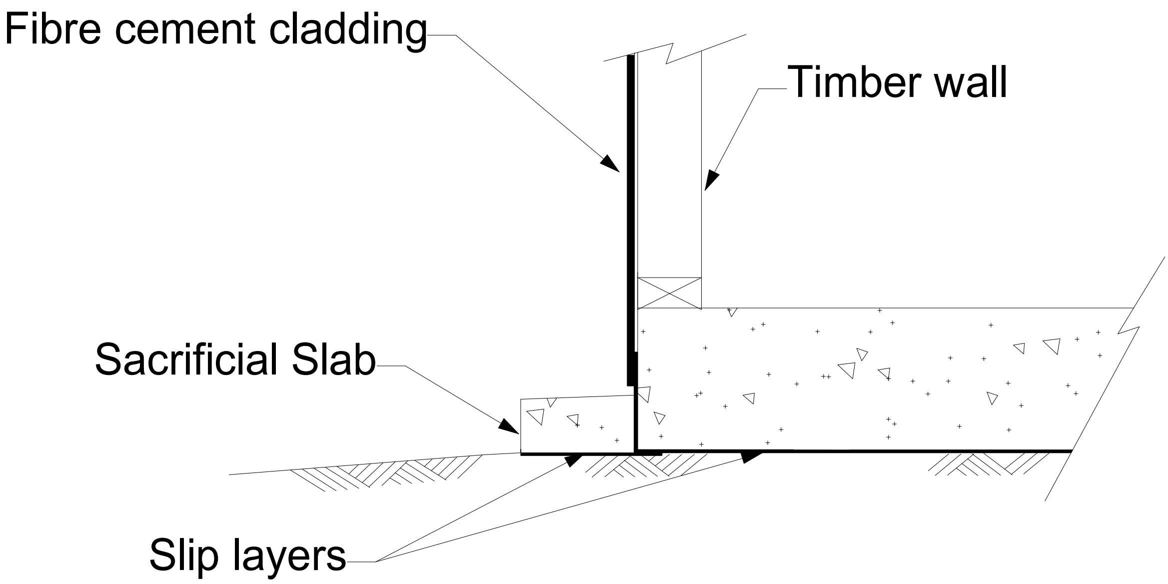


Figure 13. Variation of the system proposed by Yegian and Kadakal (2004)

4. TEST PROGRAM

4.1 Proposed base-isolation system

The proposed base-isolation system is that in Figure 12 or Figure 13. The intention is to underlay the entire building with a layer of 40 mm thick sheet polystyrene (both for insulation and to provide a flat surface), followed by the two slip layers suggested by Yegian (namely UHMWPE plus Typar geo-textile). However, as the tests reported herein showed that there was some slurry seep through the geo-textile (which affected the slip coefficient) it is proposed that a thin sheet of polyethylene (i.e. polythene) be placed on top. This was done for the subsequent tests. In a real situation, the concrete will be cast in-situ on top of the polythene. Clearances would be provided around the slab perimeter to prevent soil passive pressure from resisting slab movement. The problem of allowing building services to enter the building without being at risk of rupturing in a seismic event has yet to be resolved.

4.2 Total planned test program

Initially it had been planned to construct a 4 m long by 2 m wide base isolated concrete slab as per Figure 13 on the ground outside the BRANZ structures laboratory. This would have included construction joints between slip layer sheets. Construction problems would have been noted. The slab would have cycled under a horizontal slow cyclic deflection regime to check that laboratory performance, herein and by others, could be duplicated. The surface undulations and grit etc contaminants expected to be present in the field conditions and joints between sheets of interfacing slip layers were expected to increase the effective slip coefficients. However, before this field work was carried out laboratory tests discussed in Section 4.3 indicated that the slip coefficients would be too high for the system to be viable and thus the project was abandoned.

4.3 Laboratory test program

4.3.1 Test set-up

A 4 mm thick steel plate of size 2.4 m long x 1.2 m wide was rigidly fixed to the top of a shake table. A 2.4 m x 6 mm thick UHMWPE sheet was screwed to the plate on a 300 mm grid with the screw heads being rebated. A sheet of Typar geo-textile was laid on top of the UHMWPE sheet. A concrete slab of dimensions 1 m x 1.5 m x 150 mm was cast into the mould shown in Figure 14. The concrete was allowed to cure and the formwork removed except for the front section (foreground in Figure 14) which was retained. The bottom 20 mm of this front section was removed to ensure it did not touch the table. After stripping the formwork the Typar was wrapped around the slab to ensure the two interface sheets were taut as shown in Figure 15.

Sinusoidal motion was applied to the shake table. Motion of the slab was prevented using the two rolled hollow section (RHS) arms shown in Figure 15 and the force to achieve this was measured using a load cell on each arm.

4.3.2 Reduction of test data

(a) Calculation of the dynamic coefficient of friction

The dynamic coefficient of friction, μ, was calculated from:

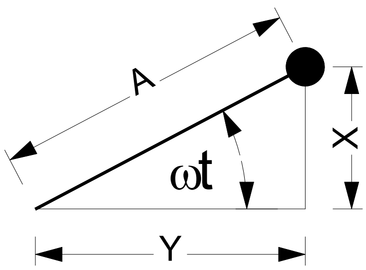
$$\mu = \frac{Sum\ of\ the\ slip\ forces\ measured\ by\ the\ two\ load\ cells}{Effective\ weight\ of\ concrete\ block}$$

The effective weight of the concrete block was taken as the measured weight including the bolted-on RHS section and one RHS arm.

(b) Calculation of block velocity

The imposed harmonic motion on the table can be represented using the rotary harmonic motion sketched below and can be expressed:

$X = ASin\,\omega t$ where A is the maximum displacement imposed and the velocity is ω radians per second.



The block velocity can be found by differentiating the above expression, giving:

$$\dot{X} = \omega A\ Cos\,\omega t$$

From the geometry of harmonic motion sketched above:

$$ie, \dot{X} = \omega\, Y = \omega \sqrt{A^2 - X^2}$$

Thus, as at any point in time the values of ω, A and X are known, the velocity $\dot{X}$ can be found.

4.3.3 Measured coefficient of friction

Table 2 summarises the measured dynamic coefficient of friction (μ). The slip layers used between the shake table and concrete block are given in the order bottom to top. The notation used is given below:

UHMWPE	Unmodified 6 mm thick Tivar ultra-high molecular weight polyethylene as screwed to the shake table.
Typar A	Typar 3601 high strength non-woven geo-textile. This was the original sheet onto which the concrete slab was cast.
Typar B	As per Typar A but a sheet directly off the roll.
Polypropylene	Non-woven polypropylene.
PTFE grease	This was purchased commercially in a tin labelled “Xtreme Performance … grease with PTFE”.
PTFE spray	This was purchased commercially in a spray can labelled “CRC dry glide dry film …. Contains PTFE”.

(a) UHMWPE/Typar A

The values of μ measured in the early stages of testing were high. This is attributed to the cement paste which leached through the Typar during the concrete pour. As the tests progressed this was worn away and the measured values of μ dropped. μ showed significant decrease with increase of velocity as shown in Figure 17 for Run 3.

(b) UHMWPE/Typar B

The values of μ measured were significantly less than for Typar A. μ was almost independent of velocity as shown in Figure 18. Runs 6 and 7 were at higher axial loads and showed that μ reduced with increase in axial load and remained independent of velocity. When the UHMWPE surface was sprinkled with 150 millilitres of water the average value of μ decreased to 0.16. The plot shows significant decreases in μ with velocity, as shown in Figure 19. However, any grit on the surface significantly increases μ and results in materials damage as demonstrated in Run 9.

(c) UHMWPE/Typar B/Polythene

These interfaces showed similar values of μ as demonstrated by Run 10.

(d) UHMWPE /Polythene

This interface gave a high value of μ as demonstrated by Run 11.

(e) Typar B/Polypropylene

This interface gave an average μ of 0.19 as demonstrated by Run 12.

(f) Polythene/Polypropylene

This interface gave an average μ of 0.19 as demonstrated by Run 14. Use of PTFE spray reduced this to 0.16 as demonstrated by Run 15 and 16. It is interesting to note that for this slip surface μ increased with velocity as shown in Figure 20. However, use of PTFE grease was counterproductive as μ increased to 0.29 and 0.30 in Runs 17 and 18, respectively.

Use of a non-taped lap joint in the polythene caused it to “bunch up” in Run 16. This did not occur in Run 12 when the polythene was on top of Typar and the Typar was lapped. Taping joints only caused a problem when the tape was on the interface of the slipping layers.

(g) UHMWPE/Polypropylene with PTFE spray

These interfaces gave an average μ of 0.3 as demonstrated by Run 19.

5. CONCLUSIONS

Many authors have advocated using a slip layer beneath a building foundation to provide base isolation. Yegian and Kadakal (2004) performed small-scale slip tests to measure the coefficient of friction, μ, of a variety of materials. They found that Typar 3601 geo-textile placed over UHMWPE gave a static and dynamic coefficient of friction of 0.10 and 0.07, respectively. This investigation considers these and other materials for use under NZS 3604 type building slabs. Such (non-isolated) buildings are designed for a base acceleration coefficient of 0.24 in Wellington and 0.12 in Auckland. Thus, the dynamic friction coefficient of 0.07 was considered to be appropriate. However, the UHMWPE is expensive (materials for these test cost \$106/m^2).

This report presents the results of moderately large-scale slip tests which were performed to measure the dynamic coefficient of friction of various sheet materials. When concrete was cast directly on Typar geo-textile the measured value of μ was large due to seepage of slurry through the Typar. The Typar sheet was replaced and the results below are for new clean sheets. The results for the coefficient of friction, μ, at the interface of UHMWPE and Typar geo-textile were disappointing as μ was approximately 0.24. This is possibly due to the moderately large scale of the tests done. The Yegian and Kadalal (2004) tests were done at normal stresses greater than 40 kPa and their plots showed μ decreased with increased axial load. The tests reported herein showed μ decreased from 0.25 to 0.21 when the axial stress increased from 3.9 to 10.9 kPa. When the surfaces were wet μ decreased to 0.16. However, unless a method of keeping the surfaces wet in practice is developed this cannot be relied upon.

Although the block tested was cast on the table where it was tested, subsequent measurements showed the under-surface to have a saucer shape profile, with the middle being approximately 1.5 mm lower than the edges. This may have increased the measured values of μ.

The block had a smooth under-surface and the interfacing sheet faces at the slip layer were clean. Tests showed that small sand particles increased the measured friction significantly. Hence, it is expected that still higher friction coefficients than measured herein would be present in real construction.

Typar to polythene and Typar to polypropylene interfacing surfaces gave friction coefficients of 0.19. Modifying these surfaces with PTFE spray reduces μ to 0.16. The writer does not advocate such treatment until reliability of this value is determined for a 50 year installation period. The PTFE grease increased μ and is therefore not beneficial.

Hence, it is concluded that none of the examined products were suitable and the project has been terminated.

Often the cost of damage to the contents of a house is of similar order to structural damage costs in a major earthquake. Thurston (2006) showed that because house contents often respond to earthquakes with a long-period rocking motion until they topple, base isolation may not provide significant reduction in damage to these contents as many of these objects themselves have a long period and resonance is a risk.

Building services, particularly water and sewerage, which cross a slip surface, are likely to rupture. Methods of protecting such services need to be developed and their effectiveness proven before using slip layers under a slab as a satisfactory base-isolation system.

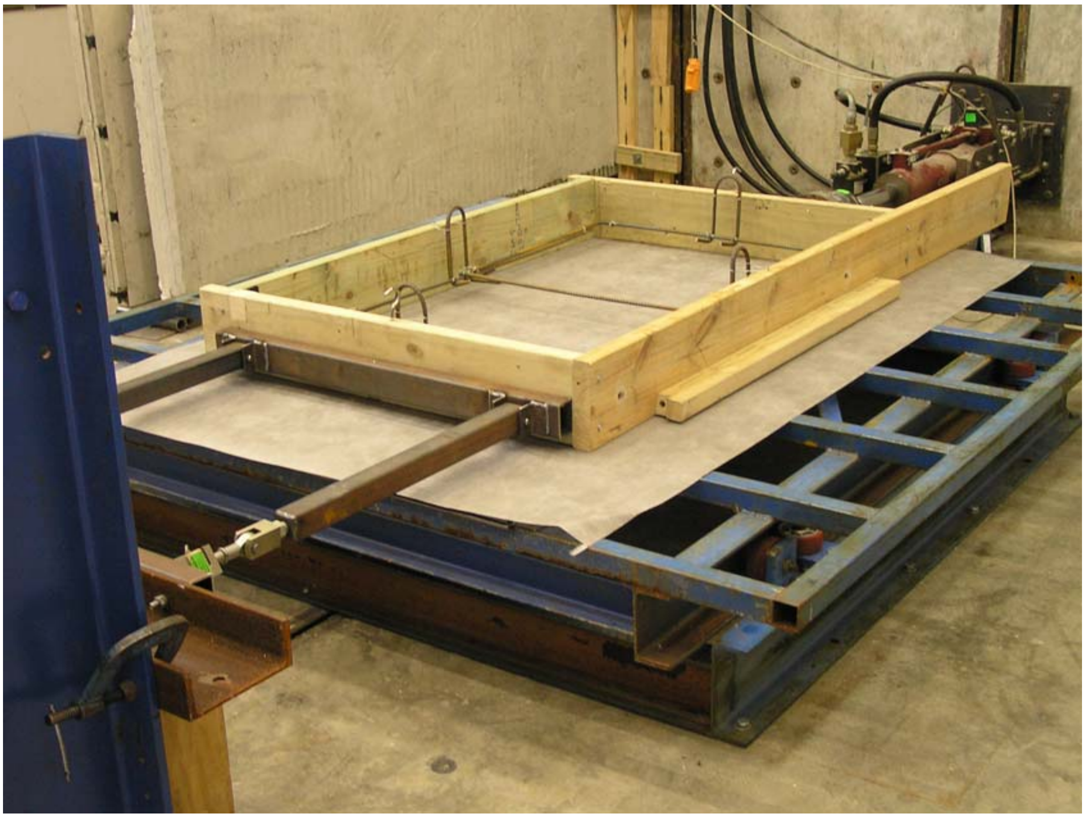


Figure 14. Formwork for casting base-isolation slab

The slab sits on Typar geo-textile which sits on UHMWPE screwed to a steel sheet fixed to the shake table.

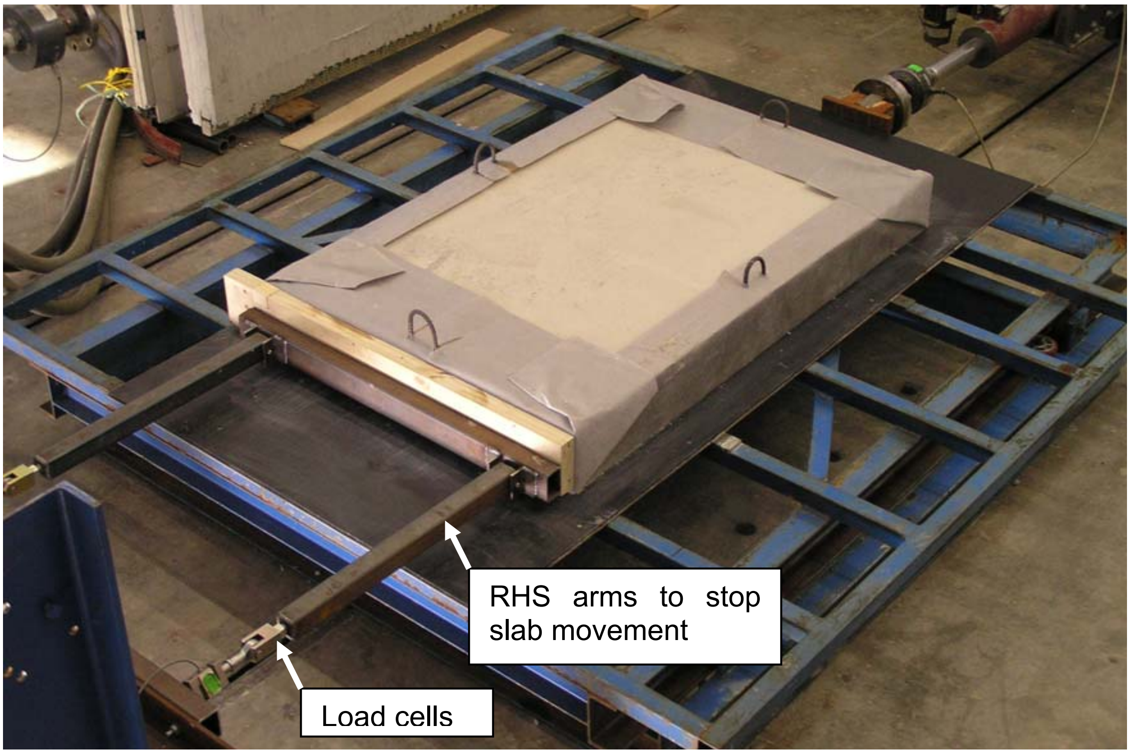


Figure 15. Set-up for the first shake table tests

Figure 16. Mass added to the shake table

Table 2. Summary of dynamic coefficient of friction values measured

Run No.	Total dist. (mm)	dyn μ	Description (arrangement and damage)
1	300	0.41	UHMWPE/Typar A. Initial half cycle $\mu \approx 0.5$.
2	6480	0.33	UHMWPE/Typar A.
3	15660	0.31	UHMWPE/Typar A.
4	5400	0.25	UHMWPE/Typar B. ie fresh sheet of Typar used.
5	4320	0.25	UHMWPE/Typar B
6	3240	0.23	UHMWPE/Typar B. Average pressure increased from 3.86 to 7.05 kPa.
7	4320	0.21	UHMWPE/Typar B. Average pressure increased to 10.9 kPa.
8	4320	0.16	UHMWPE/Typar B. Average pressure back to 3.86 kPa. Suface sprinkled with small drops of water.
9	4320	0.3	UHMWPE/Typar B. Suface sprinkled with a dessertspoon full of graded sand which passed through a 2.36 mm mesh. Some grooves formed in the UHMWPE and some small tears occurred in the Typar. The Typar was replaced.
10	4320	0.24	UHMWPE/Typar B/Polythene. A layer of polythene was placed below the block and the Typar was replaced. Both were left flat and cut 50 mm away from the edges of the block. In the first two cycles there was slip between the Typar and UHMWPE. Then in one direction the slip was between polythene and Typar - and the Typar got ejected out one end.
11	6480	0.34	UHMWPE/Polythene
12	3240	0.19	UHMWPE/Typar B/Polypropylene. The Typar was lapped by 150 mm. The Polypropylene was taped to the concrete block. Generally the Polypropylene slipped smoothly on the Typar except that the Typar did slip 130 mm at one stage to reduce the lap length to 20 mm.
13	3240	0.26	UHMWPE/Typar B. The Typar was lapped by 150 mm.The Typar slipped smoothly on the UHMWPE .
14	3240	0.19	Polythene/Polypropylene. The Polypropylene was taped to the table.
15	3240	0.16	Polythene/Polypropylene with 0.06 kg of PTFE spray. The Polypropylene was taped to the table.
16	3240	0.16	As per Run 15 but the polythene had a 150 mm lap joint which was not taped. This proved to be unsatisfactory and "bunched up" in the test. It was also found that if the joint was taped and the tape was on the top surface of the lap it operated without a problem. However, if the tape was on the underside it "bunched up".
17	3240	0.29	Polythene/Polypropylene with 0.13 kg of PTFE grease film. This new sheet of Polypropylene was taped to the table.The temperature was 15.9°C.
18	3240	0.3	Polythene/Polypropylene with dobs of 0.45 kg of PTFE grease. This new sheet of Polypropylene was taped to the table. The temperature was 15.3°C.
19	4320	0.3	UHMWPE/Polypropylene with 0.19 kg of PTFE spray.

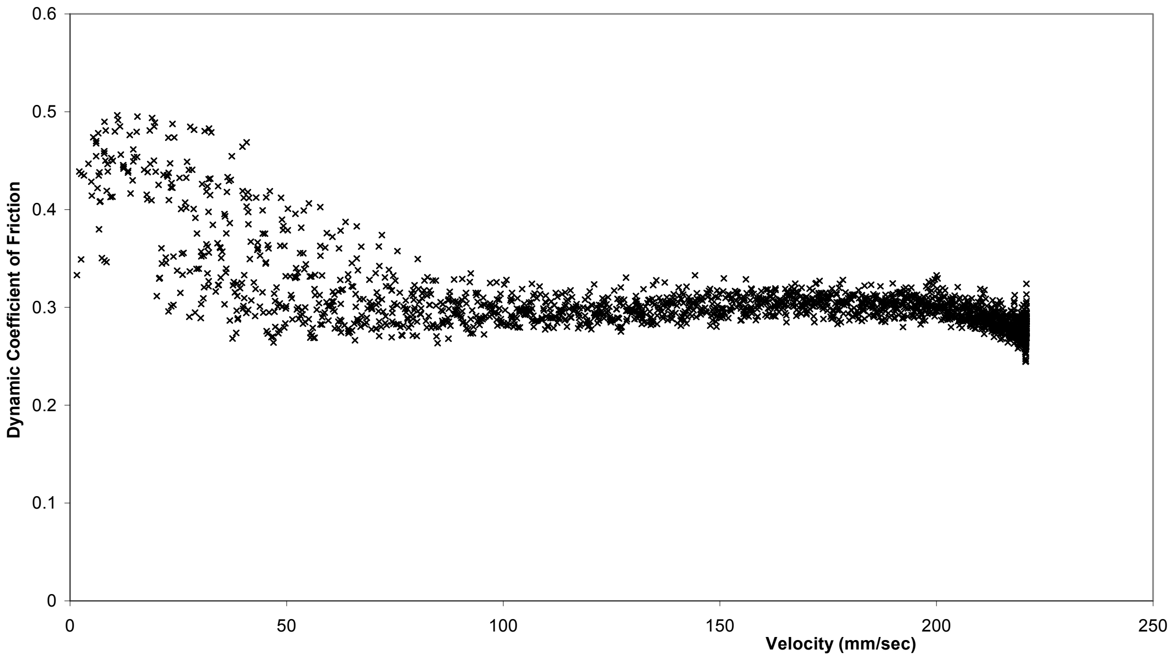


Figure 17. Coefficient of friction measured in Run 3

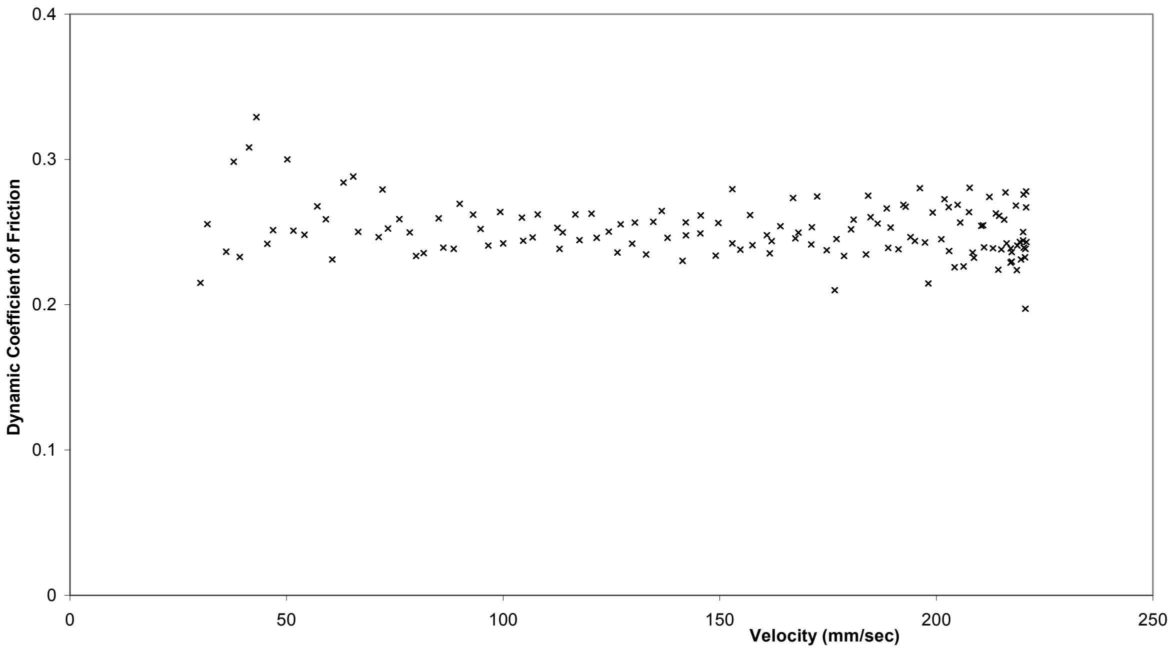


Figure 18. Coefficient of friction measured in Run 4

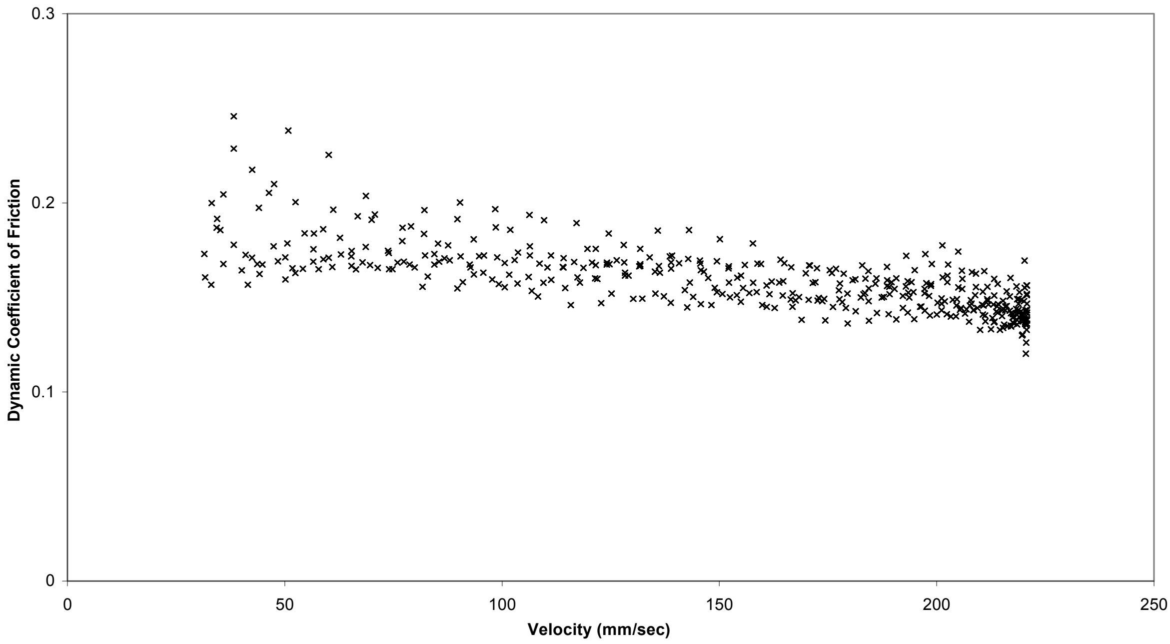


Figure 19. Coefficient of friction measured in Run 8

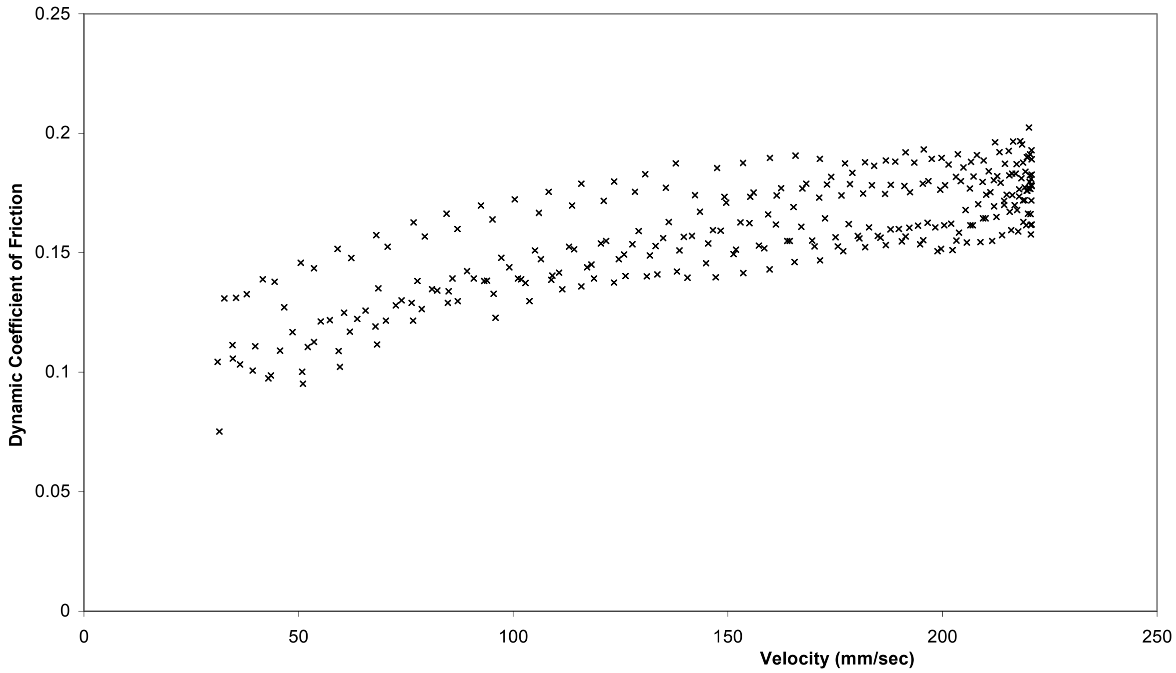


Figure 20. Coefficient of friction measured in Run 15

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