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DYNAMIC PERFORMANCE INVESTIGATION OF BASE ISOLATED STRUCTURES

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1. INTRODUCTION

Base Isolation performance can be judged as the difference in response between a building with Base Isolation and that which might have arisen had traditional foundations been used. Whilst such comparative measurements are usually impractical, this paper describes a unique experiment which provides 'insertion loss' (common terminology in Industry).

2. EXPERIMENT

An experiment to examine dynamic performance of a base isolated structure was devised around the requirements of a developer to produce high quality housing on a site above an underground railway. The site in Swiss Cottage, London, consisted of two proposed four-storey detached houses (elevation in Figure 2). A site plan in Figure 1 shows the outline of the two buildings in relation to the estimated alignment of the tunnel. The tunnel is used for Intercity train movements between Euston Station and the North-West. The tunnel depth was not known accurately, but estimated from record drawings to be some 8m below ground level to the crown.

The experimental investigation involved measurements on a test room in its un-isolated condition, which was then jacked and lowered onto three types of isolators; GERB coil springs, BTR natural rubber bearings and TICO synthetic rubber bearings. The measurements were undertaken in a way to provide the actual 'insertion loss' for base isolation. Measurements were also repeated in the completed building, both in its un-isolated, and then uniquely in its isolated condition, with the steel coil isolators being pre-stressed to allow them to raise the building itself, allowing an economical means for the test [1]. This paper presents some results for the test room only.

The test room was conceived to be one of the ground floor rooms to the final building, (see 'extent of test room' in Figure 2). This allowed it to be incorporated into the final construction. The test room is a reinforced concrete box with openings for doors and windows. The floors (5.6m span) were 225mm thick in reinforced concrete. The test room mass was about 80 tonnes, with the final building 665 tonnes, both unfactored dead loads.

Plate 1 shows a general view of the concrete test room with a view looking in a north-easterly direction across the site. The test room was initially mounted on concrete blocks (see inset to Plate 1), to represent the un-isolated case. It was then jacked and lowered on to three different sets of isolators to represent the base isolated cases, shown in Plate 2, with a view of the internal components of the steel coil isolator in Plate 3.

To establish insertion loss due to base isolation, comparative measurements were required between a 'free-field' measurement location, and the structure with its various supports. It was assumed that dynamic characteristics of the 'free-field' measurement location (Test Block) would remain constant, and therefore changes in comparisons with this datum could be attributed to the effects of alternative supports. Figure 3 describes the comparative measurements taken, with 'Insertion loss for Base Isolation = D4 – D2 or = D6 + [D5 – D2]'. Should [D5 – D2], the difference in mass effect of loading the raft via blocks or springs be small, then [D6] could be used to estimate insertion loss.

Figure 4(a) shows time histories of vertical vibration measurements with the test room on concrete blocks (measurement locations defined far right), and Figure 4(b) with the test room on steel coil springs. We can see that a significant reduction arises in the isolated test room. A spectral comparison is shown in Figure 5(a), where all three isolated cases exhibit their first mode natural frequency 5.5Hz, 9.5Hz and 12.5Hz for GERB coil springs, BTR natural rubber and TICO synthetic rubber bearings respectively. The magnification at their first resonance are broadly similar. They all also show significant reduced performance at 43Hz and 78Hz. For comparison, the response of the raft loaded with the test room on blocks (un-isolated case) is shown and also exhibits some resonance characteristics. The test room on GERB coil springs is seen to perform the best. A progressive reduction in performance occurs with the stiffer base isolation option for BTR and TICO bearings. The ramp in the transmissibility above 100Hz is due to low strength in the train vibration signal at these frequencies, where levels are dominated by instrument noise.

An important, but unanswered question always arises when considering Base Isolation. That is, what are the actual benefits of base isolation, versus the un-isolated structure. This can now be answered for all three isolator options by the simple difference between un-isolated and isolated states shown in Figure 5(b). We can note that this insertion loss shows additional frequencies of reduced attenuation at 59Hz and 88Hz compared with transmissibility measurements of Figure 5(a). These differences arise because base isolation allows the raft to vibrate more at these frequencies, whereas a traditional un-isolated structure would suppress motion, owing to the inertia/stiffness of the un-isolated building. The presence of these additional reduced performance peaks clearly represents a disadvantage of base isolation.

3. DISCUSSION

With the test room on alternative isolators (GERB, BTR & TICO) insertion loss was found to reduce for the higher stiffness isolators. In addition to the resonances at rigid body natural frequencies, significant reduced performance was seen at frequencies attributed to structural frame resonances. This shows that the dynamic characteristics of the structure are important. The value of MDOF models over SDOF to describe these characteristics is obvious. For the relatively stiffer TICO isolators, a structural frame resonance was strong enough to exceed the response of the un-isolated test room at the same frequency, implying that proper selection of isolators is also important.

The developer elected to adopt steel coil springs for the final buildings, to optimise performance although the cost difference was significantly more than the perceived difference in benefit. Approximate cost of isolators per tonne of building supported, based upon standard rates at 1996 prices are :- £33, £10.6, £6.7 per tonne for GERB, BTR and TICO respectively. Cost for GERB does however include labour cost for releasing pre-stressing bolts and for load adjustment.

Insertion loss for the test room and completed building on GERB isolators with a rigid body vertical natural frequency of 5Hz was found to be significant. Vibration was imperceptible but groundborne noise was just perceptible on occasions in a very low background. Base isolation allowed a site to be developed for quality housing.

There has been a trend to aim for lower rigid body mount frequencies, ever since the original concept of Base Isolation was introduced in 1916. Limiting factors are a concern over increased susceptibility to wind induced motion, a desire to limit the magnitude of deflection that can arise during construction, which can range from 5-30mm, and the increased cost for softer mounts.

Industrial practice for the selection and implementation of Base Isolation appears to proceed on the basis that it is at least conservative to Base Isolate, even if it is not entirely appropriate or justified.

A legal case arose in the UK in 1993, resulting from an inadequate design and specification for a Base Isolation system. The Court ruled that a statutory nuisance existed as a result of a poorly designed and specified Base Isolation system, with costs and damages awarded against the developer [1].

It is notable that the design for Base Isolation systems in the UK are never accompanied by a formal performance specification that could form the basis of some contractual agreement between the Designer of the Base Isolation system and the Developer, and be subsequently checked for compliance. Such a lack of formalism in this area of design has led to cases where Base Isolation will not always provide a cost effective means of isolation and may in some cases have a detrimental effect [1].

The additional cost of the Base Isolation 'system' and its 'knock on effects' on the structure are typically 2% to 5% of Main Contractor's tender value, where the larger ratio may arise in smaller projects (the cost of the isolators themselves being a much smaller percentage). This additional cost may therefore in some cases be unjustified, or may be better spent on alternative vibration control measures. Where Base Isolation is deemed appropriate, it may be possible to optimise performance, using a greater understanding of the performance related issues. Where good performance can be achieved, the additional cost of Base Isolation is in fact a small proportion of project value, given the scale of benefit that can be achieved.

4. ALTERNATIVE VIBRATION CONTROL OPTIONS

Alternative vibration control options, directed at the source, propagation path and receiver should be considered. The range of options may provide viable cost effective alternatives to Base Isolation, and may in some cases be used as supplementary measures to a Base Isolation proposal. No significance should be attached to the order of alternative options listed, and the list is not exhaustive.

At Source
Industrial
- Isolate source
- Undertake maintenance on plant
- Alter design of plant
- Adopt different work practice.
- Procure new plant

Railway
- Smoother running surface
- Alter vehicle unsprung mass
- Alter line speed
- Resilient rail fixings, booted sleepers, track ballast mats or a floating track slab.

Highway
- Improve quality of running surface
- Remove potholes refit loose manhole covers

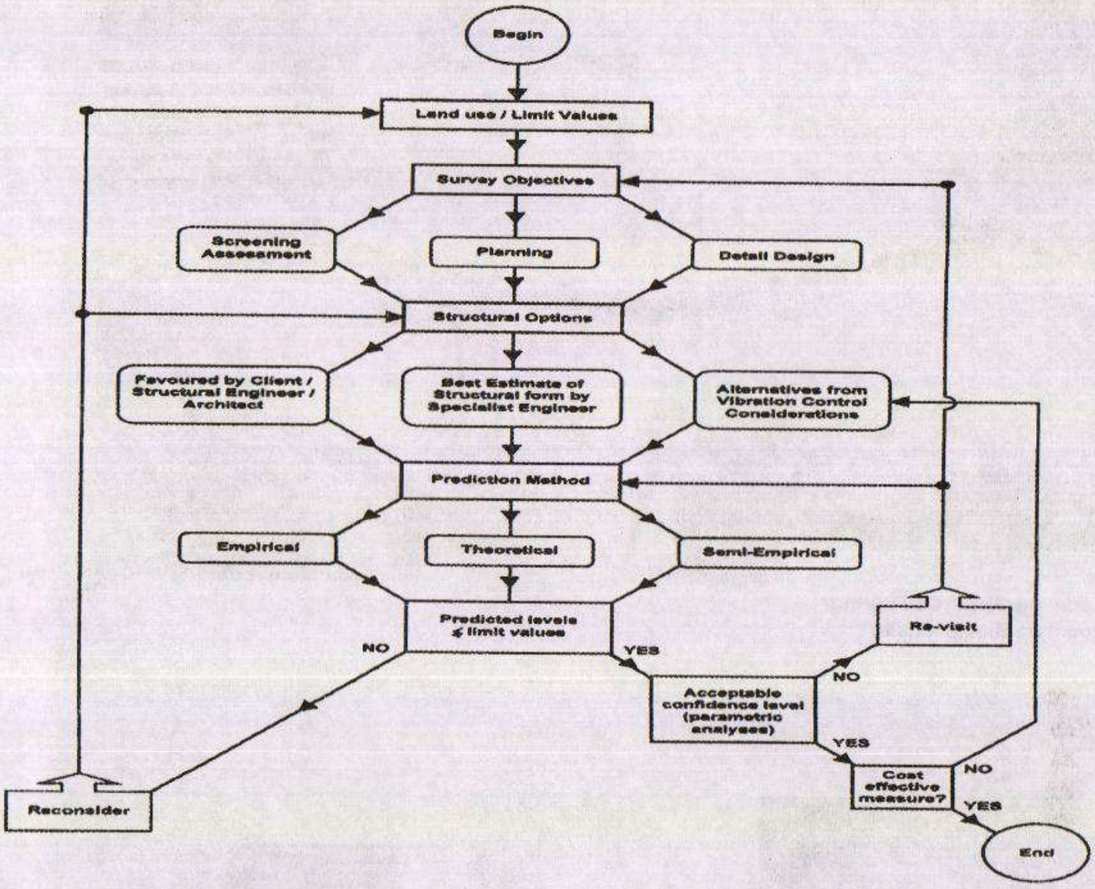
Propagation Path
- Increase propagation path, site building or sensitive parts far away from the source
- Trenches in path between source and building
- Concrete wall built into the ground between source and receiver (Impedance Wall)
- Ground treatment to stiffen a layer of soil (Wave Impedance Block)

At Receiver
- Rearrangement of plan (e.g. locate building far from source, switch location of car parks and landscaping into nearby areas)
- Reconsider use of site (commercial may be less sensitive than residential).
- Avoid floor resonance with dominant peaks in ground vibration spectrum (de-tune)
- Solid ground bearing slabs may be preferential to suspended slabs (e.g. bungalows in place of two storey dwellings)
- Unavoidable resonances targeted at frequencies of least Human sensitivity, usually requires high frequency (bandwidth may be broad, increasing risk of tuning with source)
- Low natural frequency floors may avoid tuning with source (also a narrower bandwidth), but a risk of footfall induced vibration
- A floor may be constructed on isolators off a floor below (floating floor)
- Isolate sensitive areas (box-within-a-box)
- Isolate individual items of sensitive equipment
- A dynamic system added to the primary system (Dynamic Vibration Absorber), to neutralise motion (at a specific frequency, where de-tuning cannot be achieved)
- Select structural form for optimum damping (e.g. concrete in preference to steel)
- Constrained layer floor damping treatments
- Foundations taken into strata with less vibration, decouple from soil near surface
- Sensitive equipment on ground rather than suspended floors, or equipment on foundation bearing deep in soil, and decoupled from building or soil near surface.
- Deploy traditional structural materials in a way that achieves a rigid body mount frequency comparable to that obtained with Base Isolation
- Increase path length of vibration source to increase damping (e.g. suspend floors from tops of columns rather than supported from columns directly off the ground)
- Irregular construction patterns and discontinuities in the construction
- Heavier forms of construction
- Increase background noise levels to mask intrusive noise
- Active vibration control using electromechanical or hydraulic actuators (unlikely to be a viable option in all but special circumstances)

5. INTERNATIONAL STANDARD

In the light of a lack of formalism in the procedure to evaluate sites affected by vibration, or open discussion about expected and achieved performance between Designer and the Developer, the Author proposed and drafted an International Standard with the title "Guidelines for the Measurement, Evaluation and Implementation of Base Isolation Systems to Attenuate Ground

Vibration". This draft is now under discussion with ISO/Tech Committtee108/ Working Group 3. The following flowchart describes an idealised approach to the decision making process when evaluating sites affected by Ground Vibration.



6. CONCLUSIONS

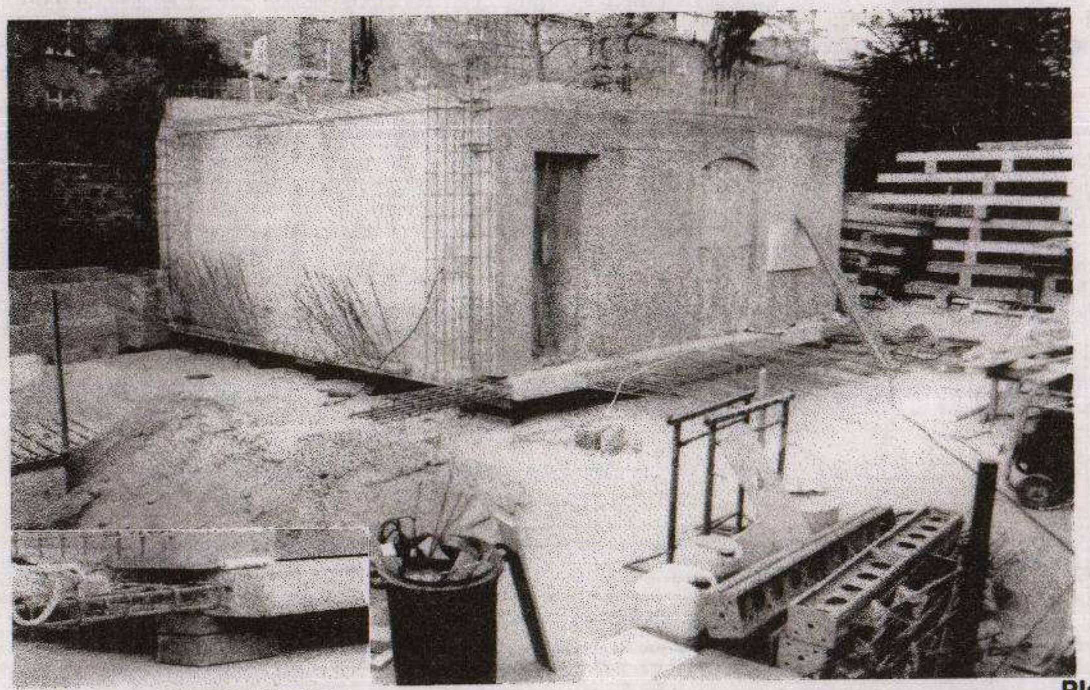
Base Isolation can provide a worthwhile improvement, although an improvement is by no means ensured. Base Isolation should therefore not be viewed as a conservative solution, in that it will always improve the situation, as there may well be alternative more effective control measures. An International Standard that addresses the design process, and important question of performance is currently under consideration and should help to focus a cost effective approach to the use of Base Isolation.

7. ACKNOWLEDGEMENTS

Thanks are due to Civil Engineering Dynamics Ltd for sponsoring the research, and GERB, BTR and TIFLEX (TICO) for supplying Isolators for the experimental investigation.

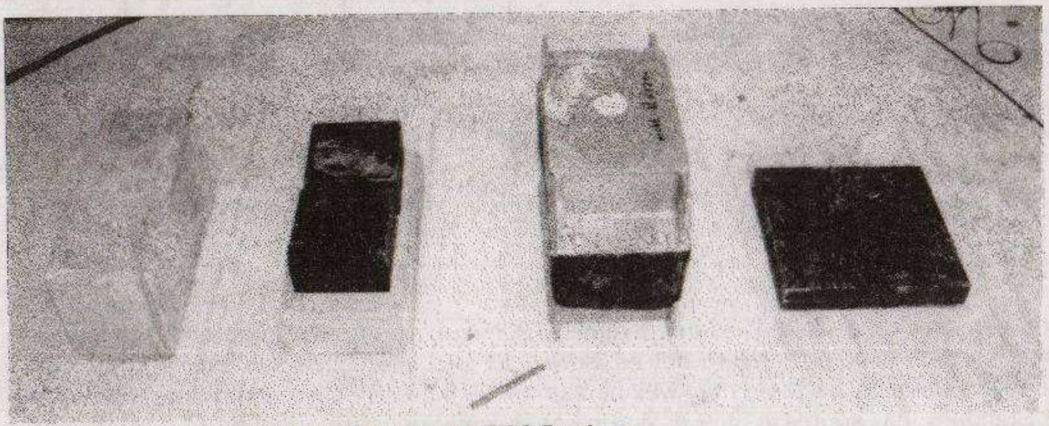
8. REFERENCE

[1] Sharif, AK., Dynamic Performance Investigation of Base Isolated Structures. Internal Reports Civil Engineering Dynamics Ltd, (83-87 Wallace Crescent, Carshalton, Sy, SM5 3SU), 1999



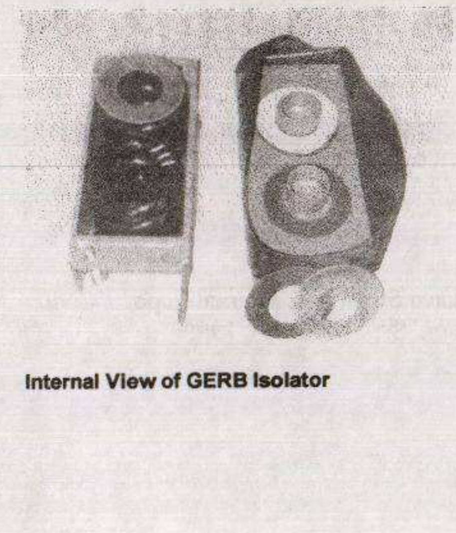
Test Room on GERB Coil Springs
Test Room on Blocks (Inset)

Plate 1



View From Left: Concrete Block, BTR, GERB & TICO Bearings

Plate 2



Internal View of GERB Isolator

Plate 3

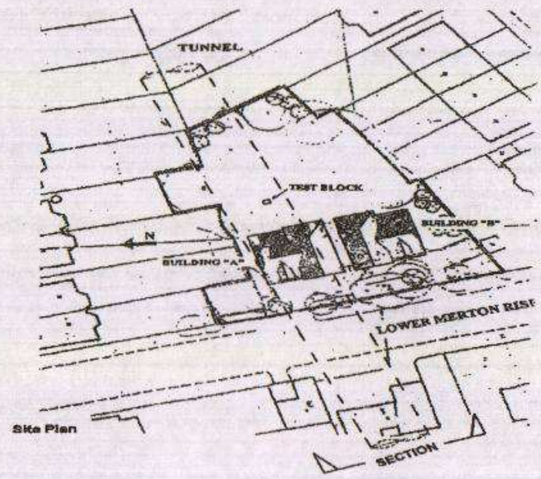


Figure 1

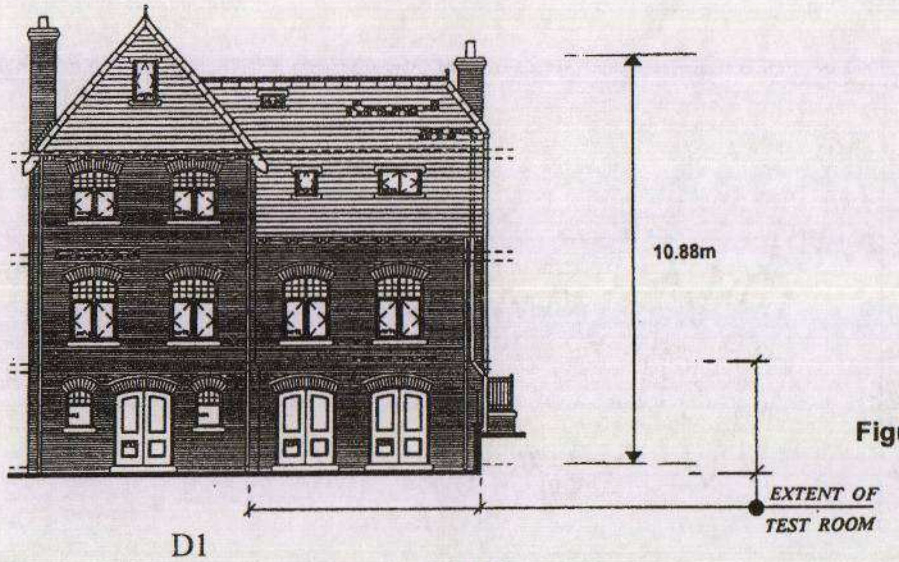


Figure 2

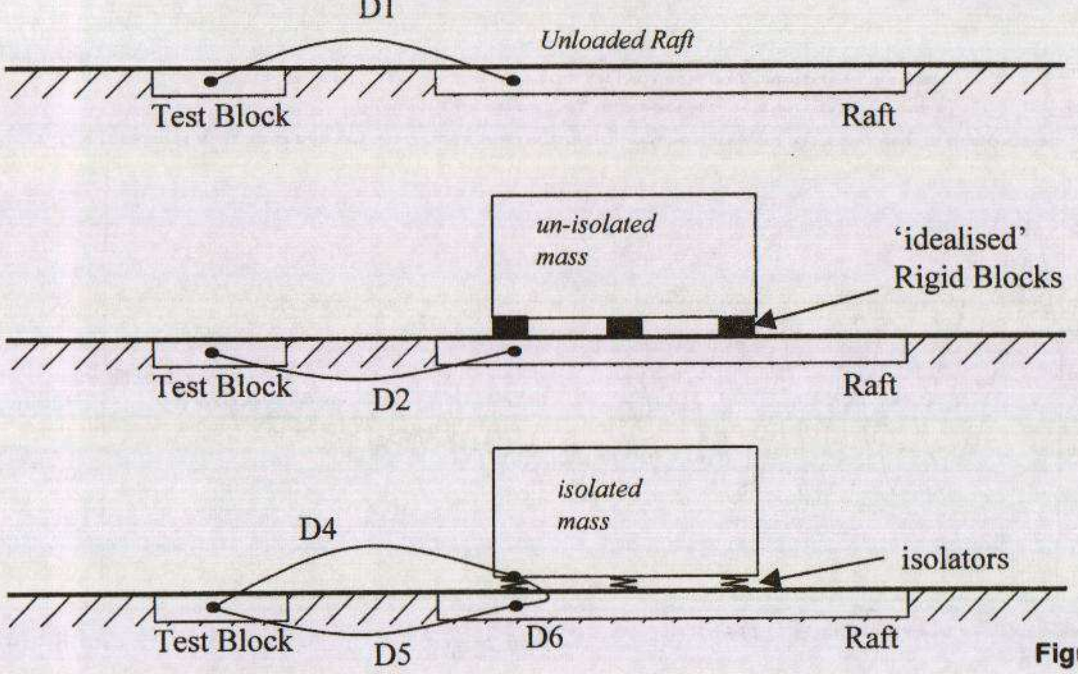


Figure 3

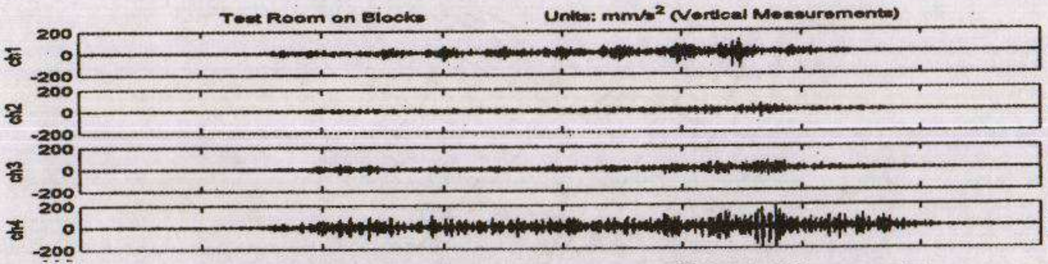


Figure 4(a)

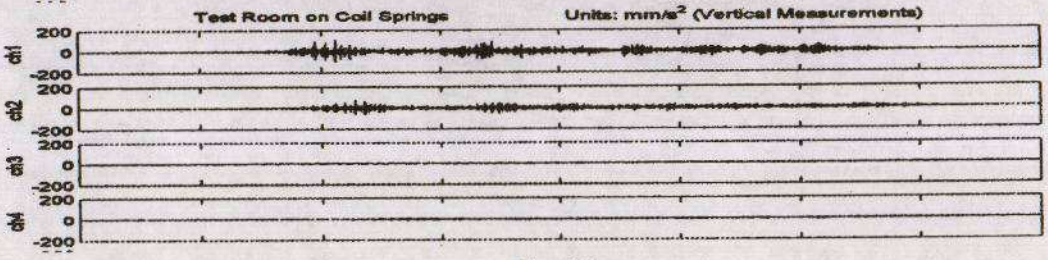
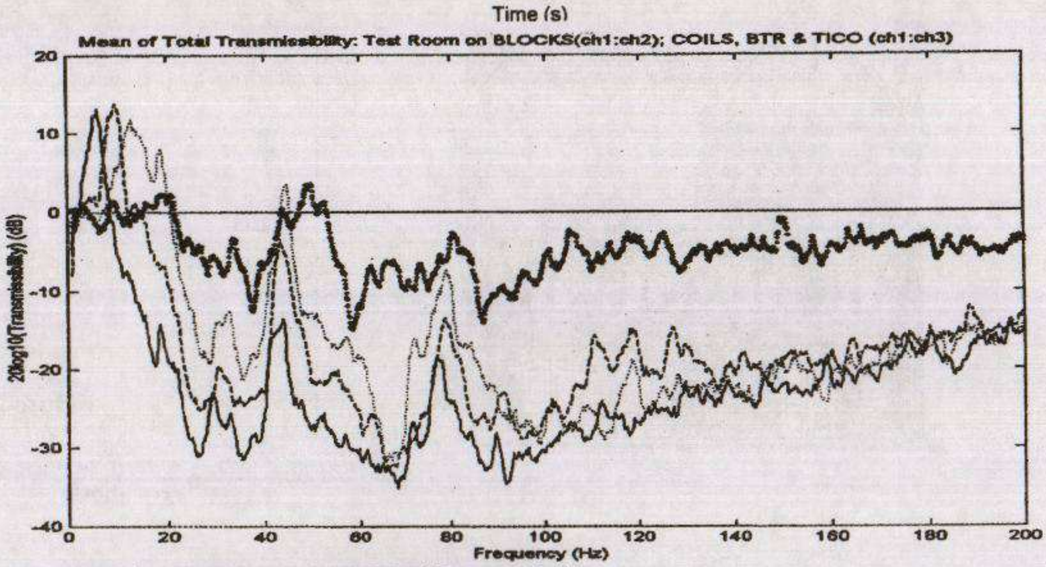
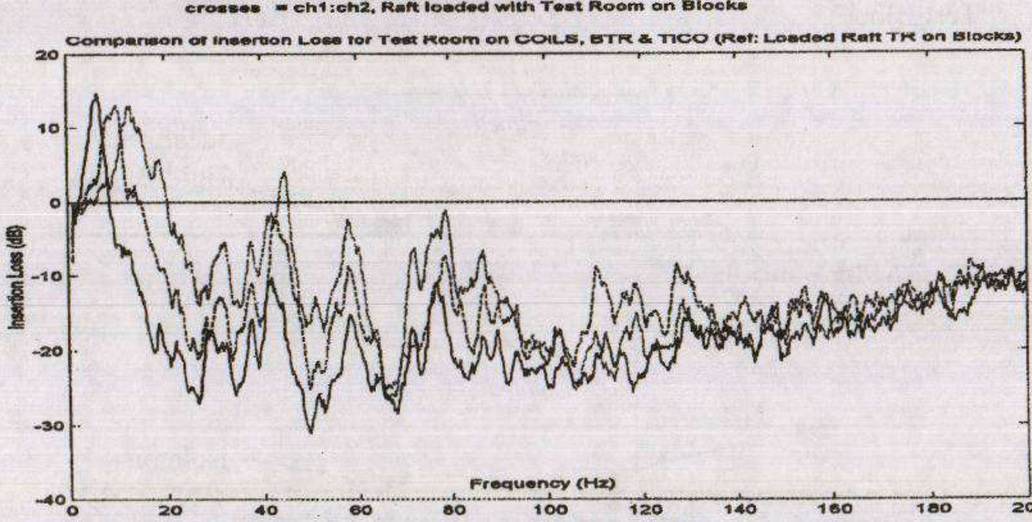


Figure 4(b)



Transmissibility solid = ch1:ch3, Test Room on Coils
dashed = ch1:ch3, Test Room on BTR
dotted = ch1:ch3, Test Room on Tico
crosses = ch1:ch2, Raft loaded with Test Room on Blocks

Figure 5(a)



Insertion Loss of Base Isolation [D4 – D2] solid = Coils
dashed = BTR
dotted = Tico

Figure 5(b)