Cancer research lab – A challenging micro-vibration design

Ahmad Bayat [1]
VACC, Inc.
490 Post Street, Suite 1427 San Francisco, CA 94102, USA

Siddharth Ashwin Mahajan[2]
VACC, Inc.
490 Post Street, Suite 1427 San Francisco, CA 94102, USA

Michael Georgalis[3]
Technical Manufacturing Corporation
15 Centennial Dr, Peabody MA 01960, USA

ABSTRACT

A donated land to three universities near a river bank, in an urban setting prompted the universities to commission a state-of-the-art cancer research lab for a prominent scientist. The site ambient vibration was measured around 2000 micro-inches/sec due to nearby highways, light-rail system, and long-term construction staging area, among others. The research lab requirements were dictated by high-end Scanning Electron Microscopes, Transmission Electron Microscopes, etc. The vibration specification for these tools demanded the environment to perform at or below 50 micro-inches/sec, a factor of 40 reduction. Typically, we desire the site ambient to lie below the vibration criterion with some margin to allow for contribution from building MEP sources. This unusual site condition presented on the surface, an impossible design challenge. We developed a multi-pronged design approach that took advantage of the soil condition at the site and designed a specialized foundation for the lab floor, and supplemented it with improvement on the tool-based isolation system by implementing an active isolation system. The final result was that the 40x site vibration was reduced to below lab vibration criterion curve of 50 micro-inches/sec. To our knowledge, the structural and foundation system of this lab is one-of-a-kind in the world.

1

abayat@va-consult.com

2

sidd@va-consult.com

3

mike.georgalis@ametek.com

1. INTRODUCTION

Three universities had received a donated site at a river bank in a busy metropolitan setting surrounded by highways, bridges, light rail traffic, and long-term construction staging and activities among others. They proposed to construct a state-of-the art cancer research facility which will house high end inspection tools such as TEMs and SEMs. Due to the above surrounding activities, the site presented itself with an unstable, active, and high ambient vibration amplitude well above 1000 micro-inches/sec. The facility vibration criterion was set to be 50 micro-inches/sec. Typically, vibration engineers wish to have an ambient level that lies below the final criterion limits with some margin to spare, such that they can use the remaining margin for facility sources contributions. This site definitely created a challenging situation for the vibration design. The challenge of reducing the site ambient by a factor of 20+ required creative solutions which resulted in a one-of-a-kind solution that on the surface might seem counter intuitive.

2. SITE AMBIENT VIBRATION

The site location plan is shown in Figure 1. The site is bounded by dense transit infrastructure, and even more traffic is expected over time. The site lies on reclaimed land, and the geotechnical report (Figure 2) indicates the presence of a three-layer soil condition: a moderately stiff surface fill layer (about 25 feet) over a very weak silty/sandy layer (down to 75 to 100 feet), with a very stiff alluvial sand/gravel below. A cross section view of the site soil layers are shown in Figure 2.

As noted, the site is surrounded by multitude of vibration sources resulting in very high vibration amplitudes and equally important unstable environment. In a typical site setting, site ambient is quite stable and the vibration variations are minimal. As Figure 3 shows, the site ambient vibration peaks around 500+ microinches/sec dominated by mid-afternoon traffic in the absence of any ongoing construction activity. With construction equipment operating, the amplitudes are well above 1000 micro-inches/sec. The "haystack" amplification in the range 3 to 12Hz depicts the soil resonance frequency of the top soil layer and possible dominating effect of traffic vibration.

We further investigated the characteristics of the site ambient by performing three case studies where a pilot caisson pile was isolated from the surface soil layer, versus a caisson pile attached to the same soil layer, and soil surface. Both piles are extended to the deeper stiff soil layer at 75+ feet. The results from this study are shown in Figure 4. As the comparison shows, the "uncased pile" vibration peak at 401 micro-inches/sec is modestly below the soil surface amplitude of 537 micro-inches/sec. On the other hand, the "cased pile" which is fully isolated from the top soil layer, enjoys from a significant vibration peak reduction at 107 micro-inches/sec. The data suggest that if one can design the cancer research lab floor such that it is fully isolated from the top soil layer, a major reduction of the ambient vibration amplitudes can be achieved.

3. LAB FLOOR CONCEPT DESIGN

It has been our experience that in every challenging engineering problem, there are equally important opportunities available to solve that problem. In this case, there exists a significant and active vibration environment on the top soil layer. On the other hand, the same top soil layer sits on top of a very weak soil layer. The opportunity in this case is to develop an isolated "island type" floor that is supported by the deeper stiff soil layer bypassing the active top soil layer. Although we typically design and recommend fully integrated slab-on-grade (SOG) with surrounding slab (i.e., no isolation) to benefit from in-plane stiffness of the larger slab, in this case that is not an option. The concept of isolating a SOG floor using a trench in all four sides about 30 feet deep supported on deep piles presents several challenges. Figures 5A-C show the "Island" slab design (plan, section and edge detail).

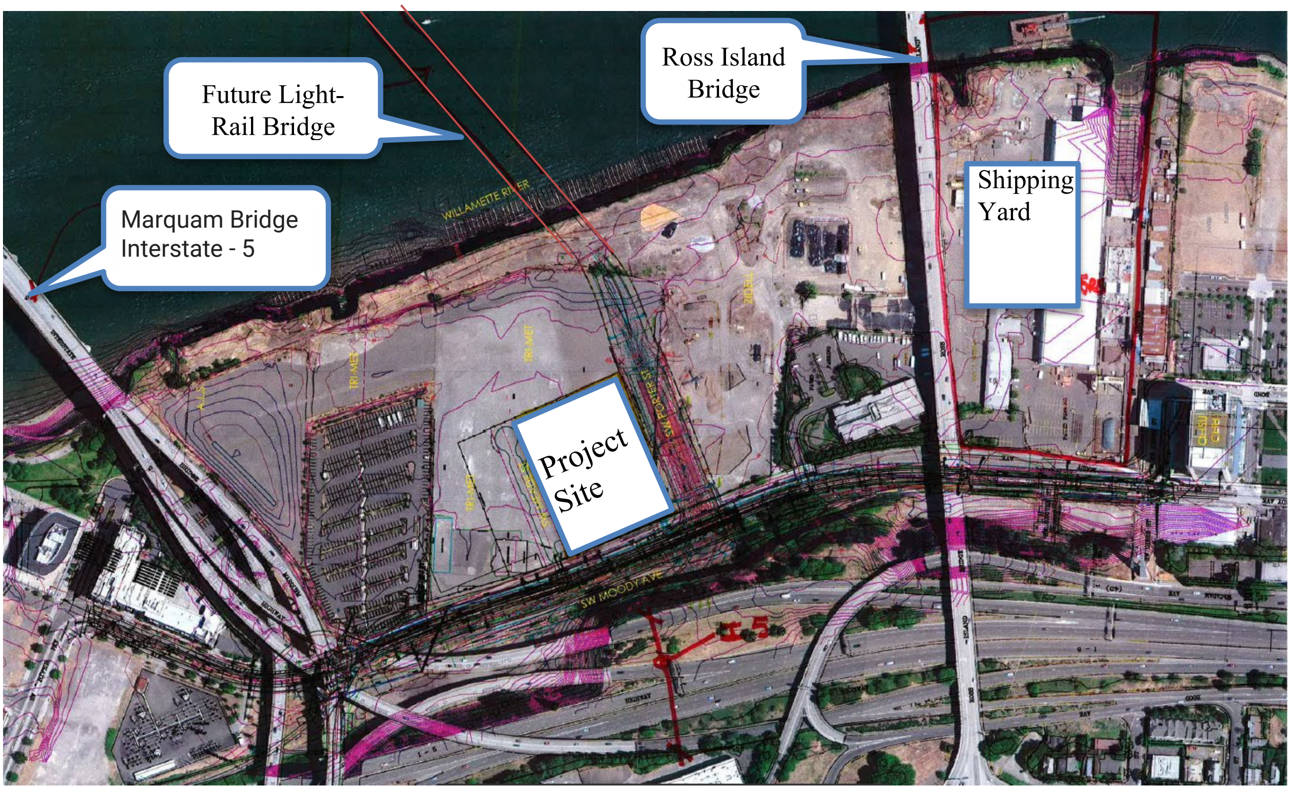

Figure 1. Site Location Plan

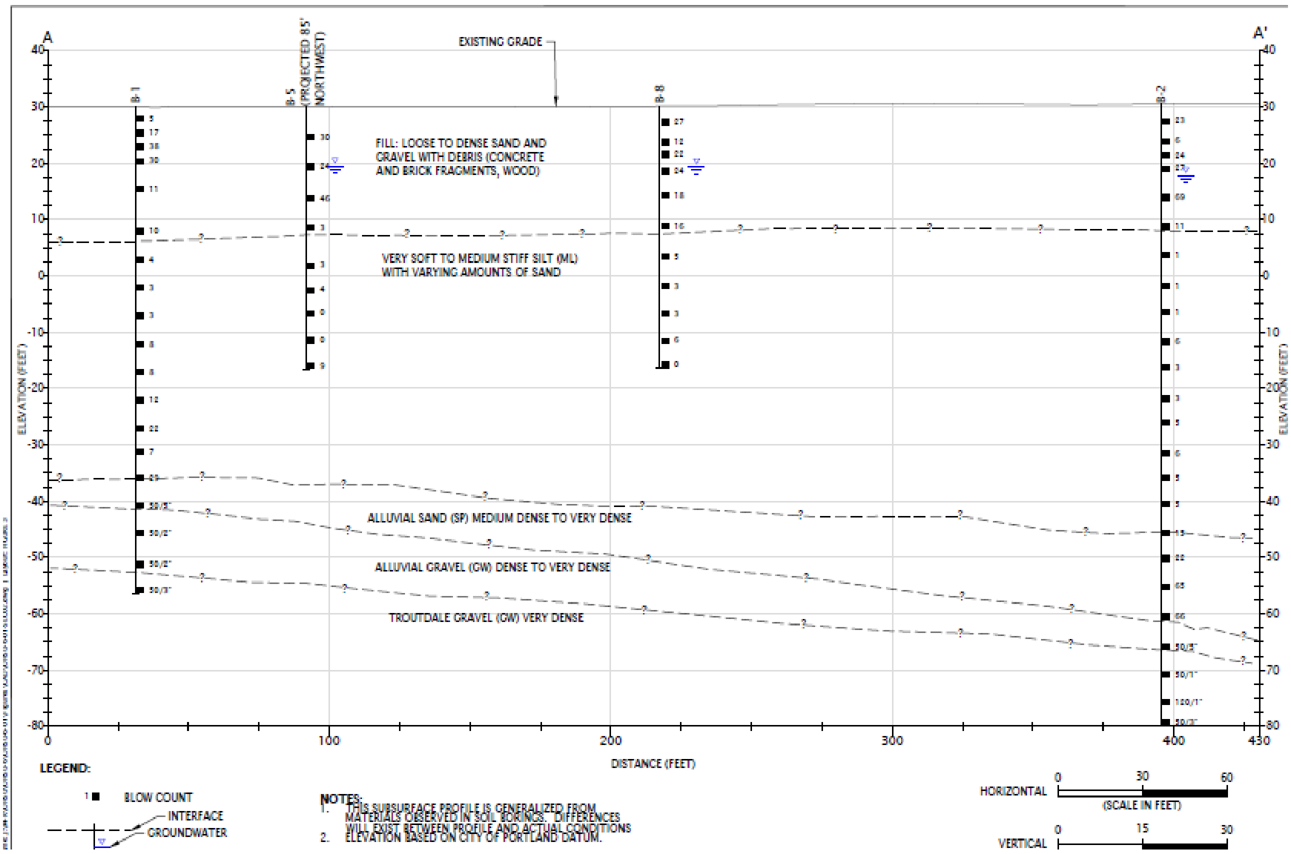

Figure 2. Geotechnical report – Soil layers with Standard Penetration Test Results

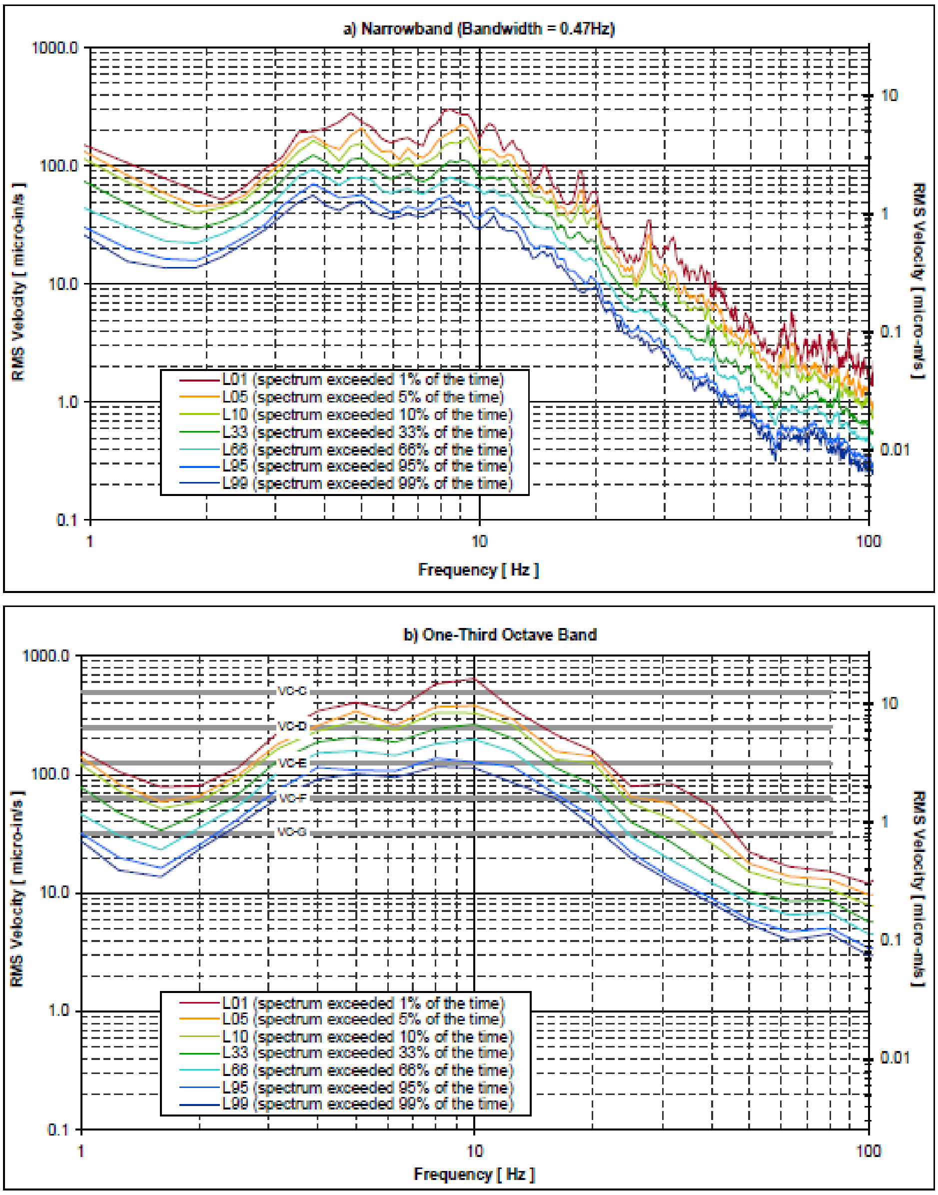

Figure 3. Site Ambient Vibration

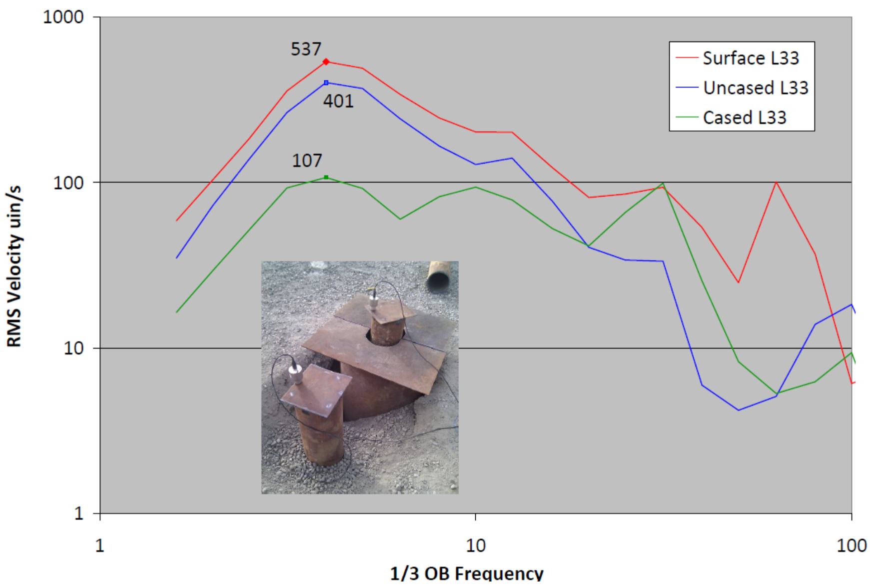

Figure 4. Site Ambient Vibration – Pilot Pile Testing

The lab floor slab was designed as a 4-ft thick slab supported on closely spaced 57 piles anchored to deeper stiff soil layer at 75+ feet. An 18-in trench was excavated along all four edges of the slab to fully isolate the slab from the top soil layer. The depth of the trench was about 30 feet. We constructed a finite element model of the slab and foundation system to determine dynamic characteristics and recommend slab and pile dimensions.

The construction of the trench was rather challenging as well and a backhoe and other equipment had to be modified to excavate the deep trench. Shallow water table was also a challenge during construction and even during facility operation as the water table could rise above the finished floor, not to mention a possible odor condition. Corrugated sheet piles were installed to provide lateral stability on either side of the trench.

We conducted as-built vibration measurements on the "Island" slab as shown in Figures 6A and 6B in vertical and horizontal directions, respectively. As expected, the "Island" Slab is performing extremely well in the vertical direction with the peak amplitude lying at about VC-F [1] or 63 micro-inches/sec. However, the "island" slab, as expected exhibits a strong cantilevered mode at 2.5Hz depicting a single degree of freedom mass-spring system associated with the total mass of the slab and about 30 feet of soil and collective lateral stiffness of 57 piles. The resonance peak is at about 500 micro-inches/sec. This resonance response must be dealt with. Lateral restraining of the slab is the solution provided it does not compromise the vertical performance gained.

We evaluated several options to arrive at introducing large clevises along all four edges. The details of the clevises are shown in Figures 5A (in red) and 5C (in blue). A total of 10 clevises were designed for each of the four edges. We modified our finite element model to determine the lateral stiffening that we needed to improve the horizontal modal response. The stiffness provided by the clevises needed to resist the dynamic mode associated with a total lumped mass of about 10 million lbs. The installation of the clevises was also challenging. Installing 40 clevises such that they develop the necessary stiffness was not a trivial task. The final installed condition must allow all clevises to work collectively to provide the required lateral stiffness to a massive slab/soil "Island".

4. FINAL "ISLAND" SLAB PERFORMANCE

We measured final as-built vibration performance of the lab floor as shown in Figures 7A and 7B, in vertical and horizontal directions, respectively. As shown, the vertical vibration lies below VC-E or 125 micro-inches/sec. The horizontal vibration performance of the slab meets VC-D or 250 micro-inches/sec.

During concept design, we had realized that the tools are utilizing passive internal isolation systems. They could possibly benefit from active isolation system such as TMC STACIS system, which was selected for this facility. Our intention was to use "Island" slab/foundation concept design to protect the slab from the very active and somewhat unpredictable vibration environment and reduce the vibration amplitudes. The structural design would be coupled with the active isolation built into the tool to arrive at the final performance below 50 micro-inches/sec criterion. The theoretical active isolation performance is accounted for in Figure 7A and 7B plots to show that the final performance at the tool level does meet the criterion limit.

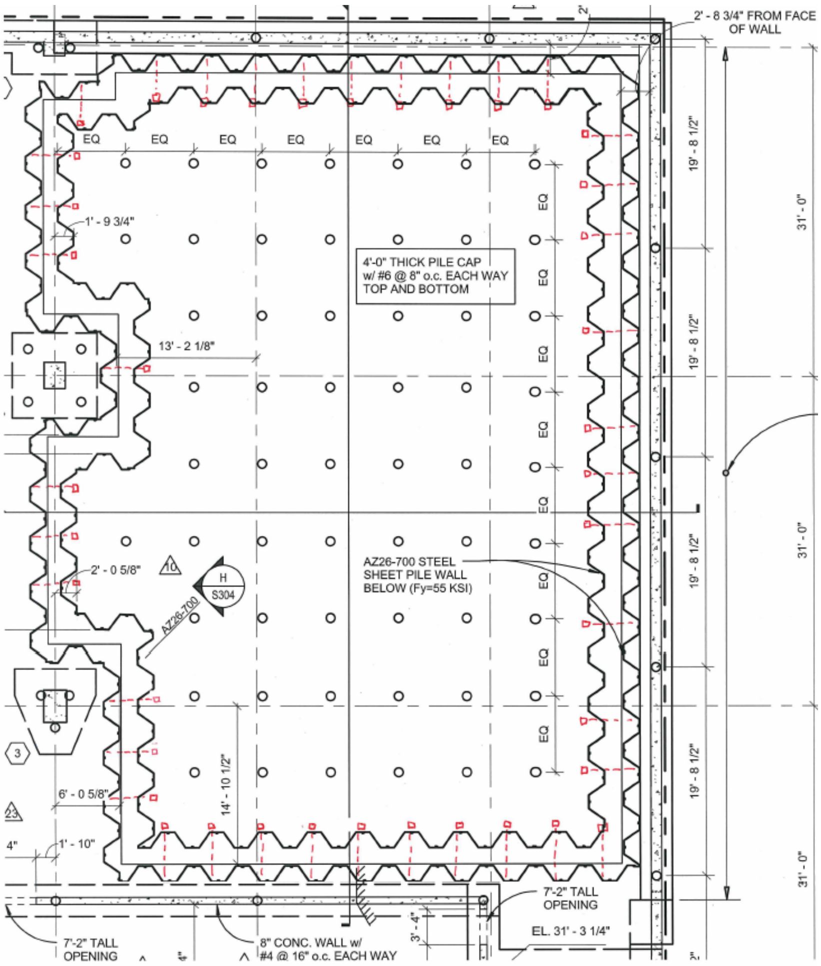

Figure 5A. “Island” Slab and Foundation Concept Design - Plan View

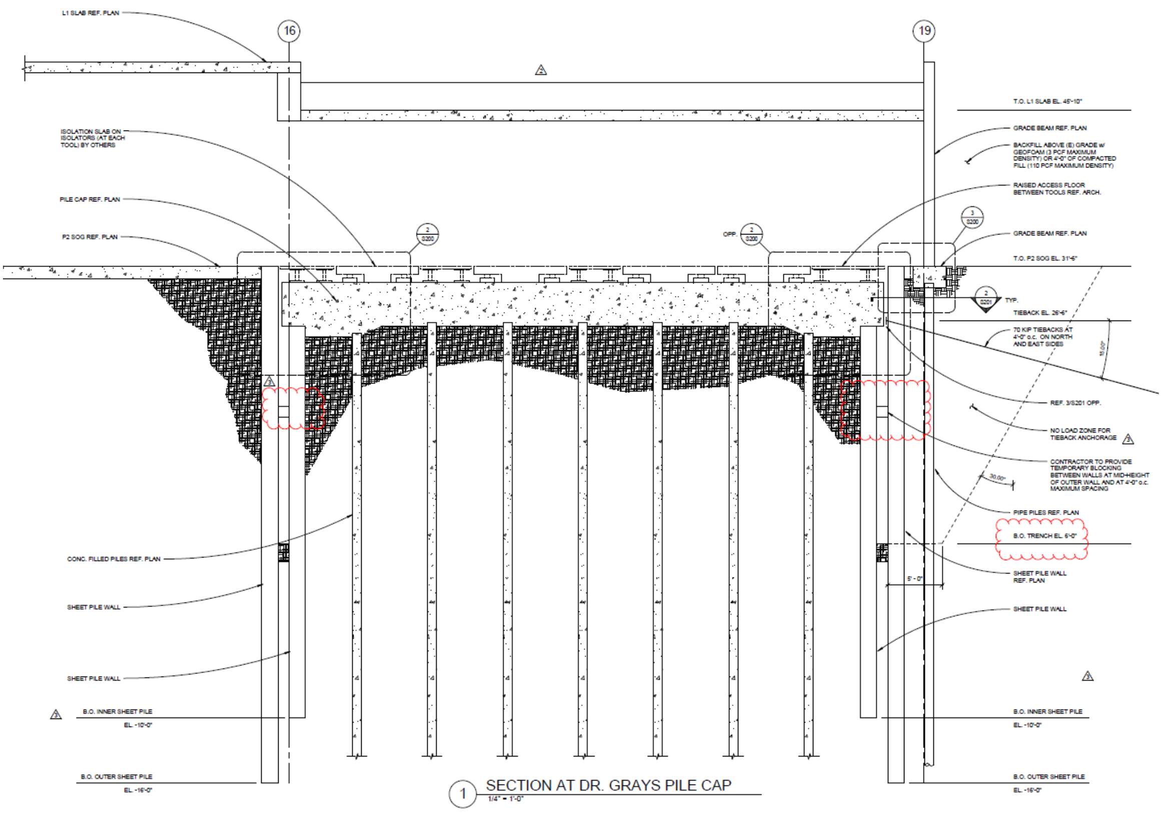

Figure 5B. “Island” Slab and Foundation - Section View

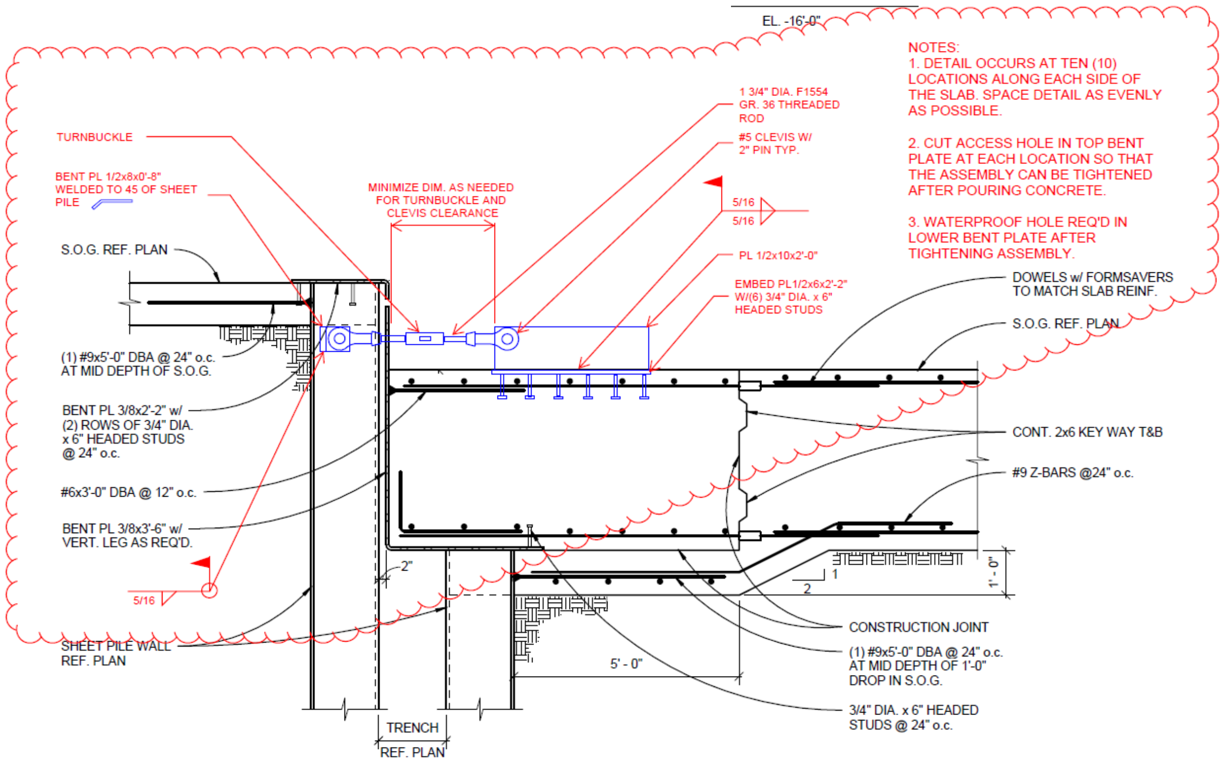

Figure 5C. “Island” Slab and Foundation - Edge Details

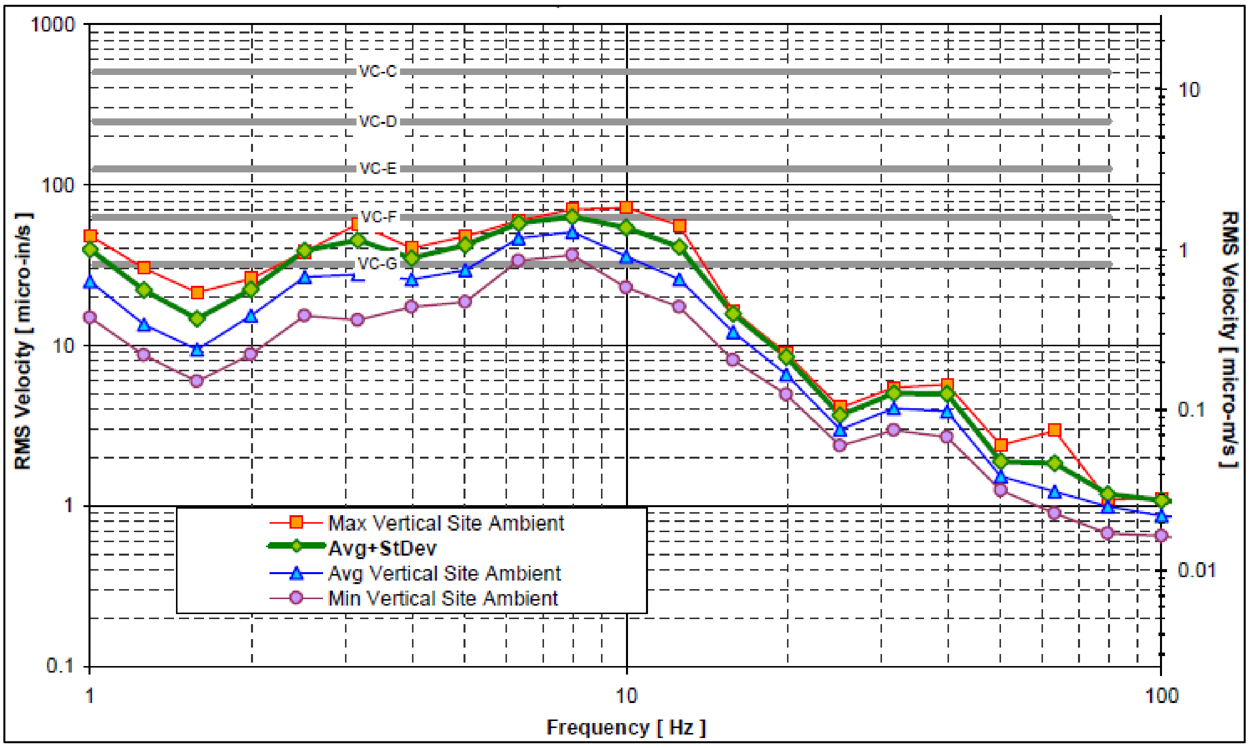

Figure 6A: As-built vertical vibration measurements on top of the island slab

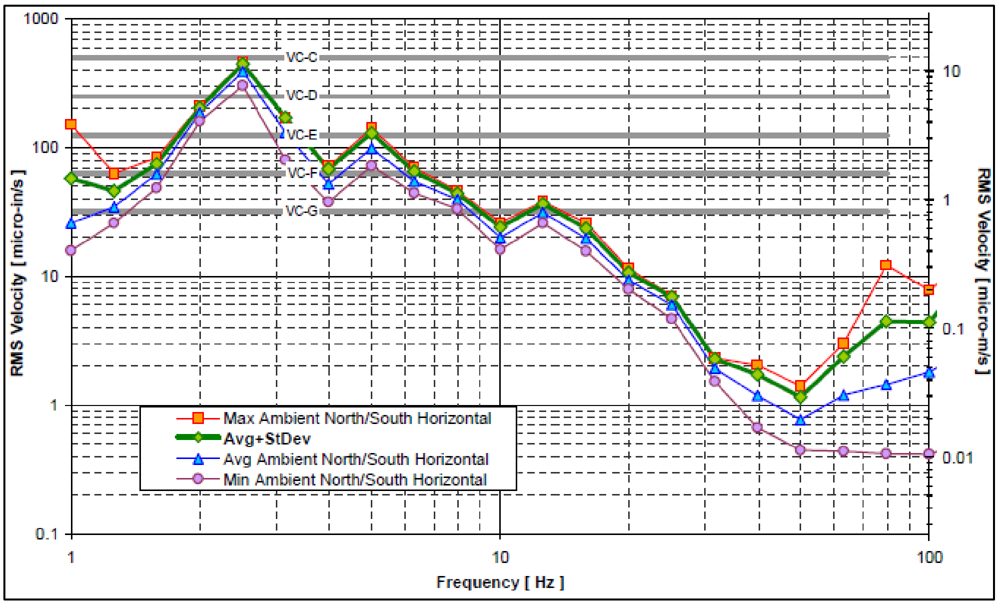

Figure 6B: As-built horizontal vibration measurements on top of the island slab

5. TMC STACIS SERIAL-TYPE PIEZOELECTRIC ACTIVE CANCELLATION SYSTEM

During our initial design of this facility, we realized another opportunity that can be coupled with the "Island" slab design to reduce the final vibration experienced at the tools. We realized that the "Island" slab concept will reduce the site ambient vibration by a factor of about 10. We coupled that with the introduction of an active isolation system at the tool mounting to gain additional reduction and meet the facility vibration limits. TMC's STACIS serial-type piezoelectric active vibration cancellation system [2] was selected. Final vibration performance after incorporation of the active system is shown in Figures 8A and 8B, in vertical and horizontal directions, respectively.
The serial-type piezoelectric architecture of a single TMC STACIS isolator (a three degree of freedom system) is shown in the 1D free body diagram of Figure 9 for simplicity. The payload, in this case a highly damped steel laminate platform supporting the tool, is supported by a stiff, passive elastomer isolator with a resonant frequency of 15-20Hz. The elastomer isolator is mounted to an inner mass with a resonant frequency much greater than 1000Hz. The inner mass is acted on by two piezoelectric actuators in the XY horizontal plane and three more piezoelectric actuators which bear the load of the entire system and payload in the vertical direction. The active cancellation is provided via feedback control of a geophone signal placed on the inner mass, whereby a corrective displacement is generated by a high voltage applied to the piezoelectric actuators to minimize the relative motion of the geophone. Using multiple STACIS isolators to support the payload, as is required in most applications, increases the degrees of freedom of the system from 3 to 6. This system architecture is uniquely suited to support payloads which contain their own isolation systems, such as the pneumatic isolation system employed by the SEMs and TEMs in this case, for two reasons. First, the passive elastomer isolates the geophone from the payload which prevents unwanted payload noise, acoustic coupling and motion from being fed into the control system. Second, the system contains no soft, low resonant frequency components. Therefore, there is no risk of coupling or instability between a STACIS isolator and the payload's own internal isolation system, and there is a minimization of low frequency input which allows the system to achieve very high gains within a broad band, enabling significant cancellation performance especially at low frequencies, starting at 0.6 Hz. An example transmissibility curve for a STACIS system is presented in Figure 10. A STACIS system was the ideal choice for this case, due to the known "island" slab resonance in the 2-3 Hz range, coupled with the risk of amplification of this resonance due to the pneumatic isolation systems in the SEMs and TEMs.

For at least one TEM supported by STACIS in this case, a highly specialized damped steel laminate platform top system was designed to optimize the system, shown in Figure 11. The TEM main frame and instrumentation was placed inside an acoustic enclosure provided by the TEM manufacturer. Even though a STACIS isolation system is designed to be impervious to payload noise, acoustic coupling and payload motion as explained above, it is good practice to reduce high frequency input (above 25Hz) to the platform top whenever possible, to minimize high frequency transfer into the payload. The platform utilized a 2-part "nested" design which placed the TEM main frame and instrumentation on an inner platform supported by STACIS isolators, mechanically separated from an outer stiff, rigid platform designed to support the acoustic enclosure. It should be noted that, even with the mechanical separation of the inner actively isolated platform from the acoustic enclosure, the independent measurements taken on the actively isolated platform top shown in Figures 8a and 8b were dominated by sources above the platform top such as tool resonances, vibration via flanking paths due to tool cables, and/or acoustic noise within the enclosure which may excite payload resonances at frequencies above 25 Hz.

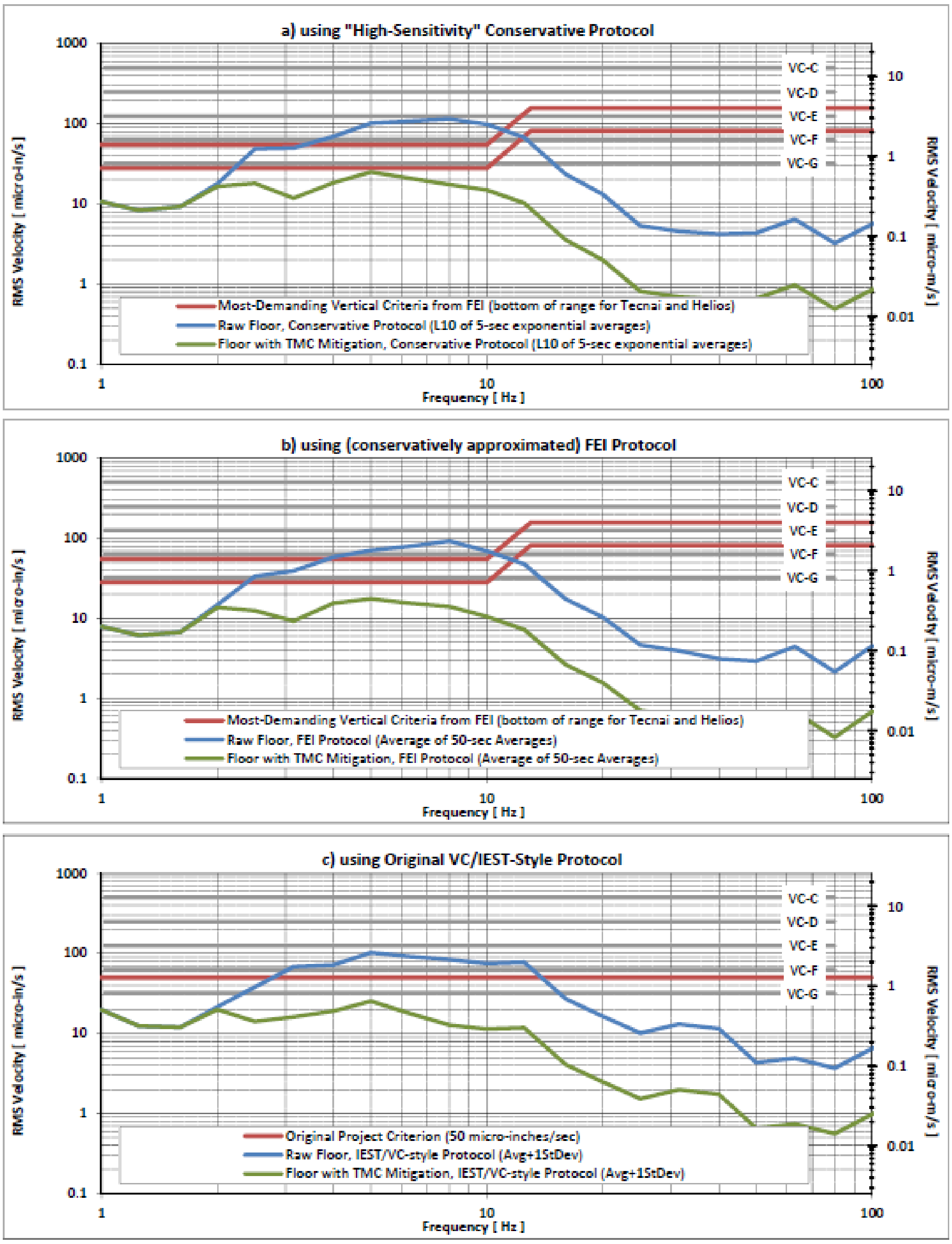

Figure 7A: As-Built Ambient Vertical Vibration measurements compared to project criteria.

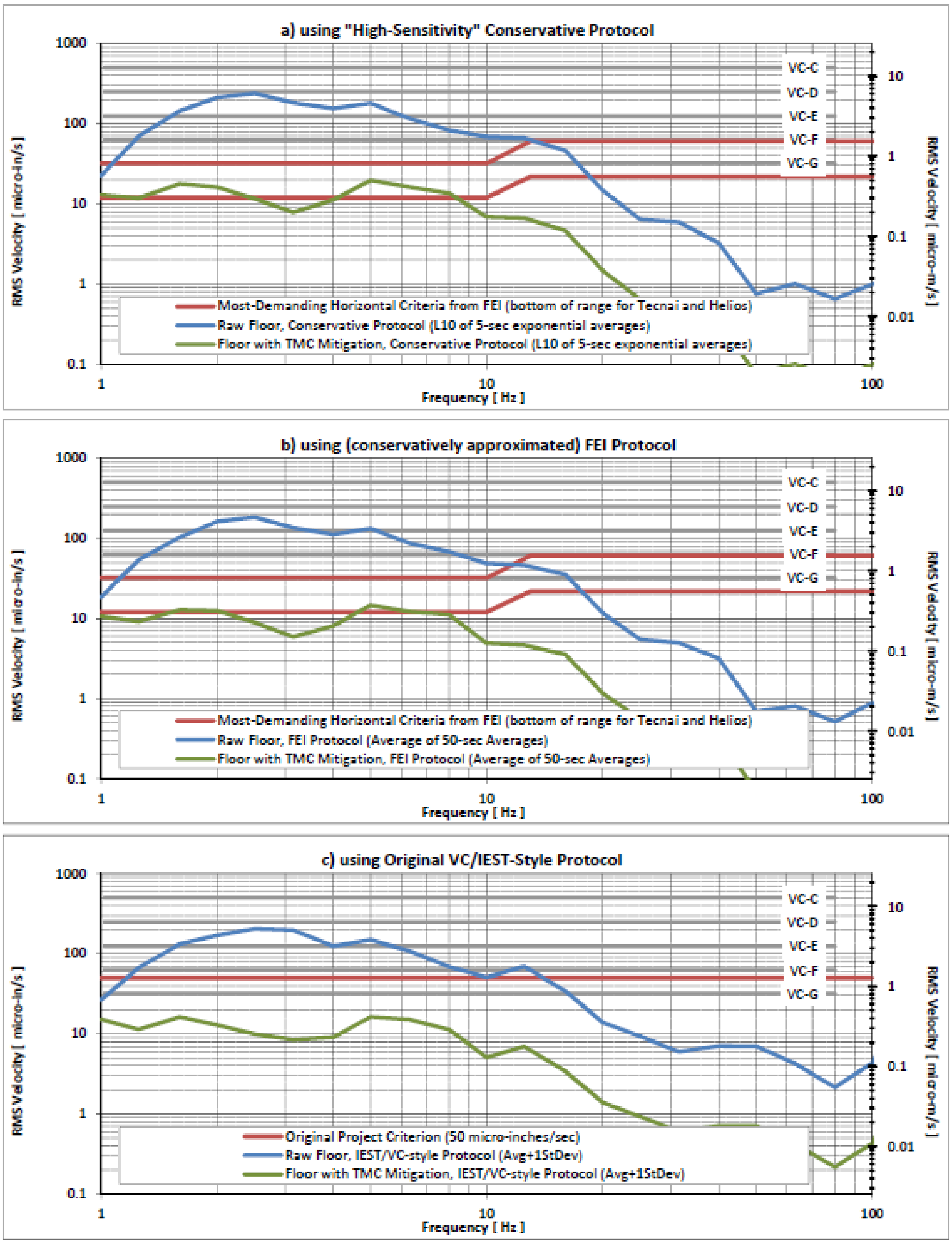

Figure 7B: As-Built Ambient Horizontal Vibration measurements compared to project criteria.

6. CONCLUSIONS

A very active site, with ambient vibration levels reaching as high as 2000 micro-inches/sec was donated to three universities to construct a state-of-the-art cancer research lab for a prominent scientist. The vibration needs of the aforementioned lab was set at 50 micro-inches/sec. The vibration design of this laboratory was a daunting task considering that, typically, one wishes to have an ambient vibration environment that is stable and its amplitude is significantly below the vibration criterion. We developed a two-prong approach for this facility. One-of-a-kind structural and foundation design was used to reduce the ambient levels by a factor of 10. Tool-based active isolation systems were deployed to reduce the final vibration performance to below the criterion.

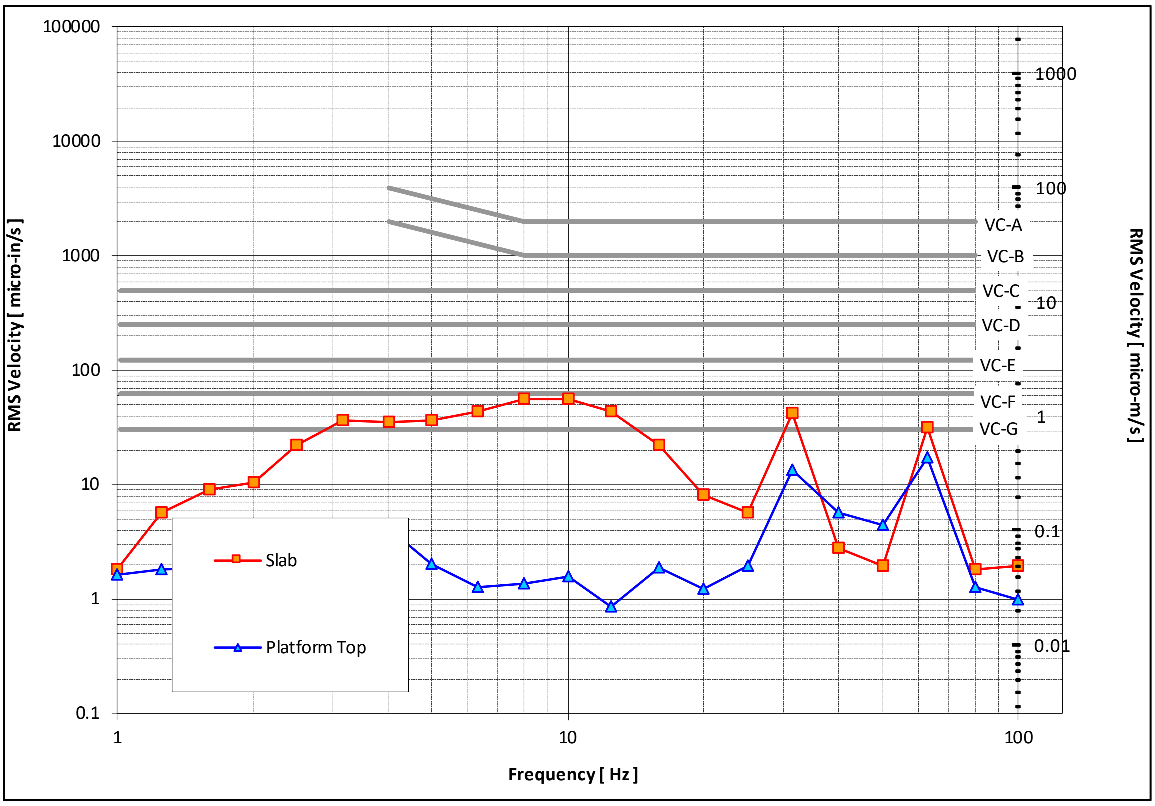

Figure 8A: Active Vibration Isolation System Measurements – Vertical

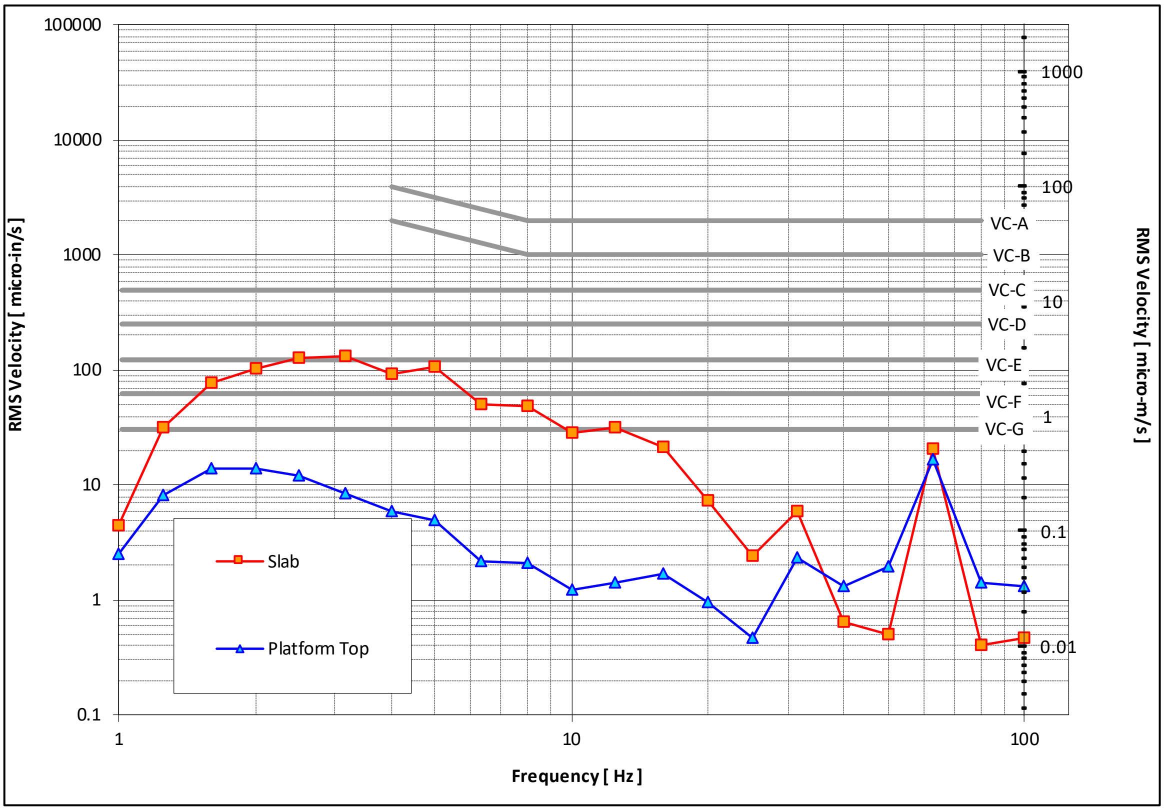

Figure 8B: Active Vibration Isolation System Measurements - Horizontal

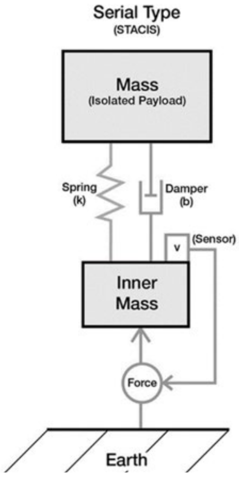

Figure 9: Free Body Diagram of a STACIS Active, Piezoelectric Vibration Cancellation System

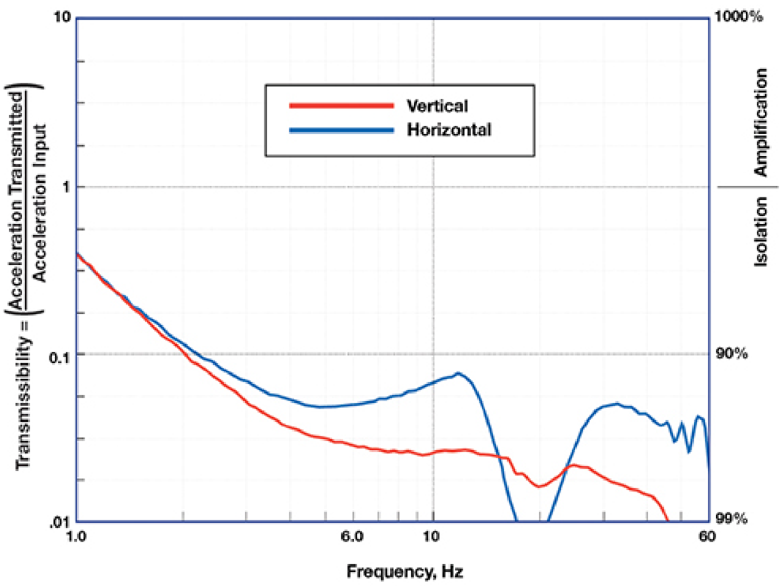

Figure 10: Typical Transmissibility Curve for STACIS

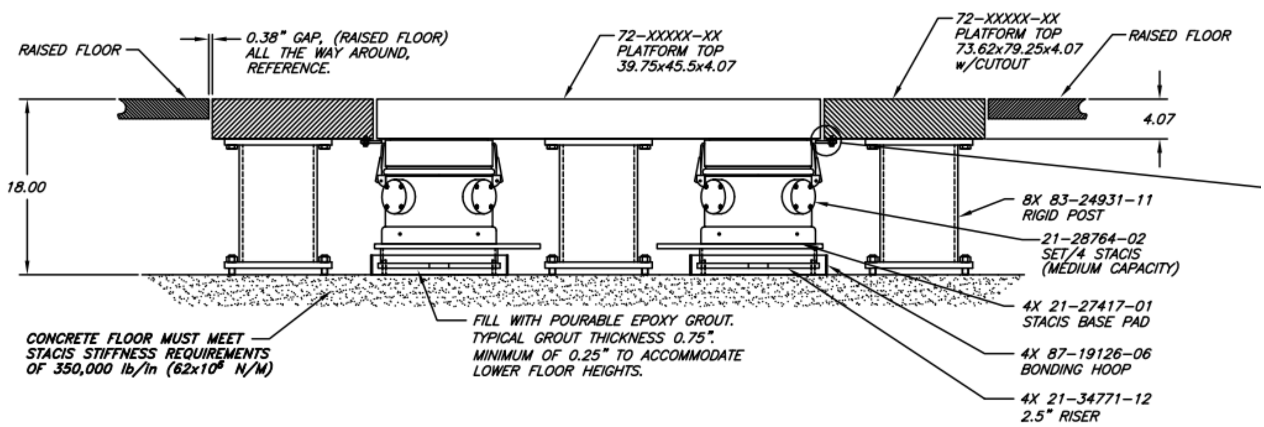

Figure 11: Elevation View of a 2-Part "Nested" platform. Inner platform supported by STACIS Isolators; outer platform supported by rigid stands.

7. REFERENCES

1. Institute of Environmental Sciences and Technology (IEST), MEASURING *AND REPORTING VIBRATION IN MICROELECTRONICS FACILITIES*, IEST-RP-CC024.
2. U.S. Patent Nos. 5823307 and 5660255