SOUNDTRANSIT
Central Puget Sound
Regional Transit Authority

NORTH LINK

PRELIMINARY ENGINEERING VIBRATION CONTROL FOR THE NORTH LINK PREFERRED ALTERNATIVE AT THE UNIVERSITY OF WASHINGTON

EXECUTIVE SUMMARY

Sound Transit
North Link Light Rail Project

April 2006
CIN 2911-0604-1680

Prepared by
Puget Sound Transit Consultants

PSTC

WILSON, IHRIG & ASSOCIATES, INC.
ACOUSTICAL CONSULTANTS

5776 BROADWAY
OAKLAND, CA
U.S.A. 94618-1531
Tel: (510) 658-6719
Fax: (510) 652-4441
E-mail: info@wiai.com
Web: www.wiai.com

PRELIMINARY ENGINEERING VIBRATION CONTROL FOR THE NORTH LINK PREFERRED ALTERNATIVE AT THE UNIVERSITY OF WASHINGTON

EXECUTIVE SUMMARY

CIN 2100-0604-1680

17 April 2006

Submitted to:

Puget Sound Transit Consultants
401 South Jackson Street
Seattle Washington
98104-2826

By:

James T. Nelson, Ph.D., P.E
Vice President

Andrew Jessop
Assistant Consultant

1 INTRODUCTION

This report assesses the vibration and ground borne noise impacts from operation of the preferred alternative of the North Link Light Rail Transit project on the University of Washington campus in Seattle, Washington. The alignment of the preferred alternative is illustrated in Figure 1. The portions of the North Link line affecting the campus include two bored tunnels of approximately 19 foot inside diameter at depths of 100 to 140 feet below grade on the campus proper, decreasing to 50 to 80 feet along the alignment extending from the boundary at 15th Avenue NE to the proposed Brooklyn Station. These tunnels would pass directly under or very near buildings on campus. However, the alignment is farther from certain core buildings identified by the University of Washington as very critical, including, among others, Bagley Hall, New Chemistry, and Physics and Astronomy. The project also would include the UW Station near Husky Stadium, a double crossover structure immediately south of the UW Station, and the Brooklyn Station between NE 43rd and NE 45th Streets. The off-campus portions of the alignment were included because these portions of the alignment would be closer to some campus buildings than the portions of the alignment that would be under Central Campus.

The purpose of this study was to re-evaluate ground vibration impacts on vibration sensitive laboratories identified by the University of Washington on the UW Seattle campus. Earlier studies by Wilson Ihrig & Associates concerned the vibration impacts of various proposed alignments.[1,2,3] These earlier efforts were based on vibration data for the Tri-Met vehicle and on limited vibration propagation data taken near the center of the campus. This current effort included collecting additional information specific to the Preferred Alternative route and Kinkisharyo light rail vehicles that would be similar or identical to those proposed for the North

---

[1] **Central Puget Sound Light Rail System, University of Washington Vibration Study, Final Report,** Wilson, Ihrig & Associates for Puget Sound Transit Consultants, 10 September 2002

[2] **Sound Transit North Link Project, University of Washington Vibration Study, Ambient Measurements, Final Report**, Wilson, Ihrig & Associates for Puget Sound Transit Consultants, 15 January 2003

[3] **Sound Transit North Link Project, University of Washington Vibration Study, Refined Vibration Predictions, Final Report,** Wilson, Ihrig & Associates for Puget Sound Transit Consultants, 21 February 2003

Link. The University of Washington is vitally concerned with preserving the low vibration environment at the various research laboratories located in basements of buildings. Because of this, a light rail system near the areas identified will require special attention to track design and maintenance practices.

2 CONTENTS OF REPORT

The report includes discussion of: vibration criteria, including the UW Thresholds, the analysis approach, new force density level data for the Kinkisharyo vehicle, new line source response data for vibration propagation on campus, predicted ground surface vibration levels at twenty-three sensitive buildings identified by the University of Washington, description of recommended vibration control provisions (mitigation) and their effectiveness, discussion of vibration compliance and monitoring, and conclusions. Three appendices with detailed field data and two appendices with detailed vibration level predictions for all potentially impacted buildings are provided.

The tests and analytical studies presented here have advanced the state-of-the-art in ground vibration prediction and analysis for rail transportation systems.

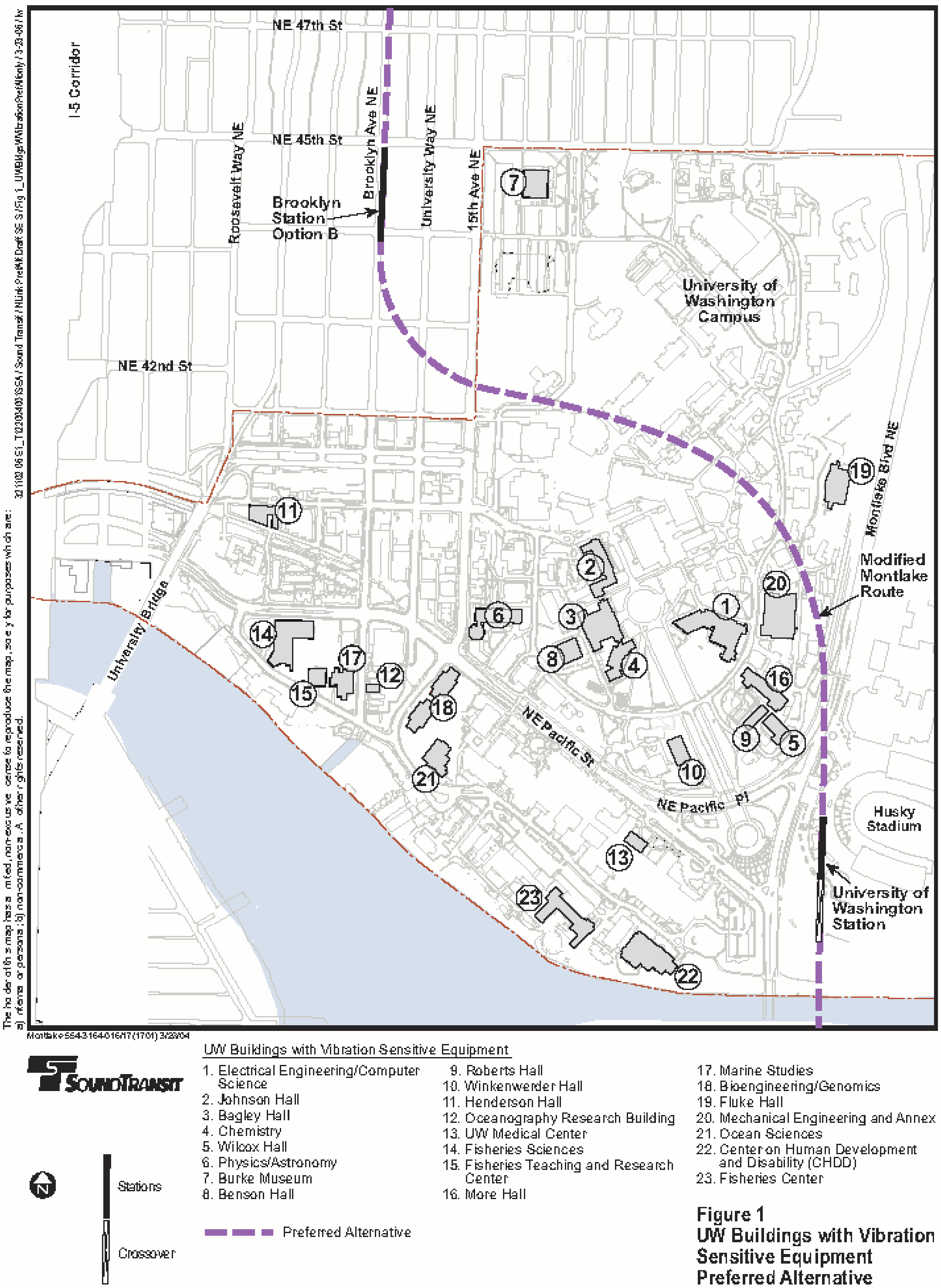

Figure 1 Map of Preferred Alignment across UW Campus

3 CRITERIA

The UW has requested that *train vibration levels be less than or equal to the current ambient vibration levels* (UW Thresholds) and that *this criteria be met using source mitigation only*. This request is described as a means of protecting both existing and potential future uses. There are two guidelines available for evaluating vibration impacts: standard Federal Transit Administration (FTA) criteria, and the Institute of Environmental Sciences (IES) criteria for very sensitive research and manufacturing equipment used in clean rooms. The FTA criteria would allow higher vibration velocity levels than the measured ambient provided by UW. The IES guidelines have been recently amended in draft form to add criteria for assessing vibration environments that are more consistent with the UW Thresholds. This report compares vibration levels to the requested UW Thresholds.

4 METHODOLOGY

The basic methodology employed for predicting ground vibration impacts is that described in the Federal Transit Administration guidelines for transit noise and vibration impact analysis,[4] augmented with numerical procedures and geophysical data. The procedure is based on a Force Density Level to represent the transit vehicle source characteristics, adjustments for various track design configurations and vibration isolation provisions, and a Line Source Response to represent the propagation of vibration from the tunnel to the ground surface. These quantities are given in terms of third octave levels in decibels.

4.1 Force Density Level Tests

The Force Density Level (FDL) is the starting point of the prediction, and represents the forces imparted by the wheel and track system to the tunnel invert. The FDL was estimated for the light rail vehicle currently being produced for Sound Transit by measuring the FDL of the Kinkisharyo vehicle used at the Santa Clara Valley Transportation Authority. This vehicle is similar to the

[4] **Transit Noise and Vibration Impact Assessment,** U. S. Department of Transportation, Federal Transit Administration, April 1995.

Kinkisharyo vehicle being procured for Sound Transit. The field work involved measuring ground vibration responses at three test sites, measuring ground vibration velocities for the Kinkisharyo vehicle at several speeds at these sites, normalizing the velocity data to obtain the individual FDLs, energy averaging the FDL's, and adjusting the results for track type.

The FDL was found to contain a prominent peak in low frequency vibration at about 8 to 10Hz for speeds of the order of 50 and 55mph. At 50mph, the peak is most prominent in the 8Hz third octave band, while at 55 mph the peak is most prominent in the 10Hz third octave bands. The FDL third octave band spectrum is at a minimum at about 16Hz, and thereafter rises to a maximum at a frequency of about 40 to 80Hz due to track and wheel-set resonances. The low frequency peaks in the data reflect a resonance of the primary suspension of the VTA vehicles. This in combination with the wheel and truck passage frequency determines the spectral peak frequency at 8 to 10Hz.

The estimated FDL is similar to FDL's for other similarly constructed light rail transit vehicles with chevron primary suspensions, and is near the upper end of the ranges observed for these types of vehicles. Indeed, we believe that rail roughness and undulation amplitude, and wheel truing standards achieved by VTA may play a greater role in the test results than is currently defined. One recommendation of this report is for further investigation of these and other low frequency vibration issues during North Link final design.

4.2 Line Source Estimates

The Line Source Response (LSR) is the ground vibration velocity in decibels at a receiver relative to the Force Density Level of the train, and is a measure of how the vibration propagates through the soil. The LSR is a function of train length, frequency, distance from the tunnel, tunnel depth, soil stiffness, damping, and layering. Third octave LSR's were calculated from vibration propagation test results obtained at four boreholes on the University of Washington campus, distributed along the Preferred Alternative alignment. The tests necessarily include the effects of source depth, horizontal offset, soil stiffness, damping, and layering. The tests do not include the effects of the tunnel. Tunnel soil coupling is usually negligible at low frequencies, but does cause attenuation of vibration at frequencies in excess of perhaps 50 to100Hz, depending on tunnel wall mass, tunnel size, and soil stiffness. This approach is based on the assumption that the soil is homogeneous in the horizontal direction, so that the measured response is purely a function of radial distance from the borehole and depth.

The original intent was to use field data for all distances from the alignment, but background vibration masked the responses at distances beyond 300ft. At 800ft and beyond (locations including Bagley Hall, Chemistry, Physics etc.) there was no evidence of vibration energy arrival from the 300lb hammers used to test for LSR amidst the background vibration and instrumentation noise. Background vibration also masked the short range response at frequencies below 10 Hz. The difficulty in measuring LSR's at a distance on campus was due to stiff soils and a deep source. (This is actually an indication of low response to vibration forces, a favorable indication with respect to the potential for impact.) Consequently, a seismic reflectivity model was used to calculate detailed responses from measured down-hole vertical shear wave velocity profiles obtained on the campus. These numerical calculations were compared to the field data. There was some under prediction at low frequencies, possibly due to background vibration and noise during field testing. Overall the agreement was quite good, validating both the experimental and theoretical procedure.

The differences between the numerical model calculations and field test results at short range were added to numerically calculated long range LSR's for distances in excess of 300ft. That is, the numerical seismic model was used to extrapolate measured short range transfer functions to large offsets for the purpose of determination of the LSR. The measured LSR's were employed for predictions within 300ft from the Preferred Alternative alignment. The extrapolated LSR's are believed to be conservative, because conservative assumptions concerning soil loss factors were employed during computation.

5 VIBRATION PREDICTIONS

Vibration levels were predicted for the Preferred Alternative for both a standard design configuration with typical resilient direct fixation fasteners and for a design that included speed reductions and track vibration isolation.

5.1 Unmitigated Vibration Impact Analysis

The predictions of unmitigated ground vibration caused by the North Link Line were based on the following assumptions about the system design:

Standard Resilient Direct Fixation Fasteners: Bonded natural rubber fasteners used between rail and tunnel invert.

Rail Condition: The rails were assumed to be of similar condition and quality to those employed at the San Jose VTA where the FDL tests were conducted.

Vehicle: The vehicle was assumed to be of the same configuration and design as the Kinkisharyo vehicle of the San Jose VTA system, for which FDL data have been collected and used for prediction. The first opportunity to test this assumption will be in late 2006 or 2007 when Sound Transit will be able to test its own vehicles.

Slip-slide control: Traction control during acceleration and braking (a standard provision to control wheel flats and roughness and thus control vibration and noise).

Four-car train consist: Four-car train consists were assumed. The overall length of the train would be 396 feet.

Simultaneous Operation of Two Trains: Simultaneous operation of trains in both directions at the point of closest approach to the receiver was assumed.

Train Speed: The maximum predicted levels for all speeds between 30 and 55mph were estimated for the alignment on campus. The assumed speed range was limited to 40mph along the curve between 15th Avenue NE and the Brooklyn Station due to operating limits on train speed on the curve.

Southbound (or downhill running) trains could reach 55mph consistently. The speed of northbound trains (uphill running) would vary depending on acceleration, degree of vehicle loading and number of cars in the consist. The southbound track is slightly closer than the northbound track to most of the sensitive buildings on campus except Fluke Hall.

Slightly lower levels of vibration (2 to 3dB) would be expected for single trains or for train operating at different speeds. The simultaneous train assumption is most relevant for receivers located at the center of curvature of the large radius curve of the campus alignment, such Bagley Hall. Simultaneous passage of trains at short range receivers, such as Mechanical Engineering or Wilcox Hall, would occur for a small fraction of train passage event, primarily depending on train headways.

5.2 Mitigated Vibration Impact Analysis

In addition to the assumptions listed above, the following mitigation strategies were evaluated in relation to the UW Thresholds:

> *Train Speed:* 30mph
>
> *Track Isolation:* Discontinuous Double Tie Floating Slab track combined with standard DF fasteners, with design resonance of 12 to 16Hz, extending from the north end of the UW Station to the campus boundary at 15 Avenue NE. High compliance direct fixation resilient fasteners of dynamic stiffness 80,000lb/in between the southern end of the campus through to the north end of the UW Station, and from the campus boundary at 15th Avenue NE through the Brooklyn Station.
>
> *Moveable Point Frogs:* Moveable point frogs installed at the double crossover located south of the UW Station.
>
> *Double Crossover Isolation:* High compliance direct fixation fasteners supporting the switch frogs and crossing diamonds at the double crossover located south of UW Station.

The floating slab considered here is a double tie design with design resonance frequency of about 16 Hz, selected to avoid the low frequency peak in the FDL at 8 to 10Hz for 55mph trains.

A 5Hz floating slab was suggested by the UW's consultant. However, the performance of a 5Hz system has not been documented, and there are risks of amplifying the vibration peak at 8 and 10Hz due to interaction between the vehicle suspension and the slab. A 5Hz floating slab could still be considered for implementation during final design should additional analyses indicate a need for greater vibration isolation at low frequencies.

Predictions of vibration with high compliance resilient direct fixation fasteners were based on theoretical curves of fastener vibration isolation as a function of stiffness. These curves have been well established and are consistent with measurement results obtained at various systems. The fasteners may amplify low frequency vibration below about 25 Hz by about 1 or 2 decibels but above about 30 or 40 Hz, the high compliance fastener would reduce vibration and ground borne noise by about 5 to 7 decibels relative to standard direct fixation track.

6 IMPACT ANALYSIS

Impacts are described below relative to the UW Threshold vibration velocity levels provided by the UW. These thresholds were derived by the UW from ambient energy mean third octave vibration levels measured over relatively short durations of about twenty seconds at basement floors. Variation and fluctuation of this average ambient vibration may occur, and may be of the order of several decibels over the course of a day, depending on traffic, operating condition of building mechanical equipment and so forth. The range of fluctuation could be of the order of 3 to 6 decibels between successive 20 second samples in specific third octave bands. In many cases, the ground vibration fluctuation due to North Link line trains would not be discernable from background vibration unless the ground vibration due to the trains exceeded the ambient background vibration energy by roughly three decibels.

6.1 Predictions for standard resilient direct fixation track

Ground surface vibration levels were computed for standard direct fixation track with simultaneous passage of two (northbound and southbound) trains and compared with the UW Thresholds. Without mitigation, the predicted ground surface levels exceed the UW Thresholds at fifteen buildings identified as sensitive by the UW:

- New Electrical Engineering
- Johnson Hall
- Bagley Hall
- New Chemistry
- Wilcox Hall

- Physics & Astronomy
- Burke Museum
- Benson Hall
- Roberts Hall
- Winkenwerder Hall
- UW Medical Center - Cyclotron
- More Hall
- Fluke Hall
- Mechanical Engineering Building/ Mechanical Engineering Annex
- Center for Human Development and Disability (CHDD)

The uncertainty in the vibration level predictions is about 6 decibels.

6.2 Mitigated Vibration Impacts

Ground surface vibration levels were computed for the vibration control provisions outlined above and compared with UW Thresholds. The predicted ground surface levels with mitigation exceed the UW Thresholds at five buildings identified as sensitive by the UW:

- Wilcox Hall
- Roberts Hall
- More Hall
- Fluke Hall
- Mechanical Engineering/ Mechanical Engineering Annex

The following are recommended during final design to further understand the predicted low frequency effects:

1) Measurement of the FDL of the actual Sound Transit Kinkisharyo vehicle.

2) Investigation of rail straightness and wheel run-out on wayside ground vibration.

3) Evaluation of rail grinding effectiveness in controlling rail undulation.

4) Further evaluation of a continuous floating slab such as offered by GERB.

The results indicate that ground vibration at low frequencies (8 and 10Hz) would remain nearly the same as without the floating slab track, while ground vibration at high frequencies above 20 Hz would be highly attenuated. The predicted high frequency vibration levels exceed the UW Thresholds at the five buildings above. However, the floating slab track would limit the high frequency third octave rms vibration velocity levels to approximately 40dB, or 100micro-in/sec. The highest predicted high frequency level is 43dB at Mechanical Engineering Annex, located at 9ft horizontally from the proposed alignment. Predicted low frequency vibration levels are less than 40dB, or 100micro-in/second, at these buildings. These levels of vibration would be suitable for scanning electron microscopes, long path laser beams, and other highly sensitive instruments, and would be suitable for semiconductor manufacturing at the highest resolutions.

Figure 2 identifies the buildings at which predicted ground vibration levels exceed the UW Threshold with installation of a 16Hz floating slab track and high compliance direct fixation fasteners, and restriction of train speed to 30mph. The locations of the floating slab track and high compliance fasteners are indicated in Figure 2.

6.3 Predictions for ground-borne noise on campus

Although this report is concerned primarily with vibration impacts on campus, estimates of ground-borne noise levels are also provided. The levels of ground borne noise with standard direct fixation fasteners are predicted to exceed a criterion of 40dBA for some classrooms, and a criterion of 35dBA in some libraries. These impacts would be in buildings located very near the Preferred Alternative alignment. Examples include classrooms at Mechanical Engineering Annex, Smith Hall, and Kane Hall, and the Engineering Library, Oedegaard Undergraduate Library, and Suzallo Library. However, no ground borne noise impacts would occur with the vibration isolation provisions proposed, regardless of train speed.

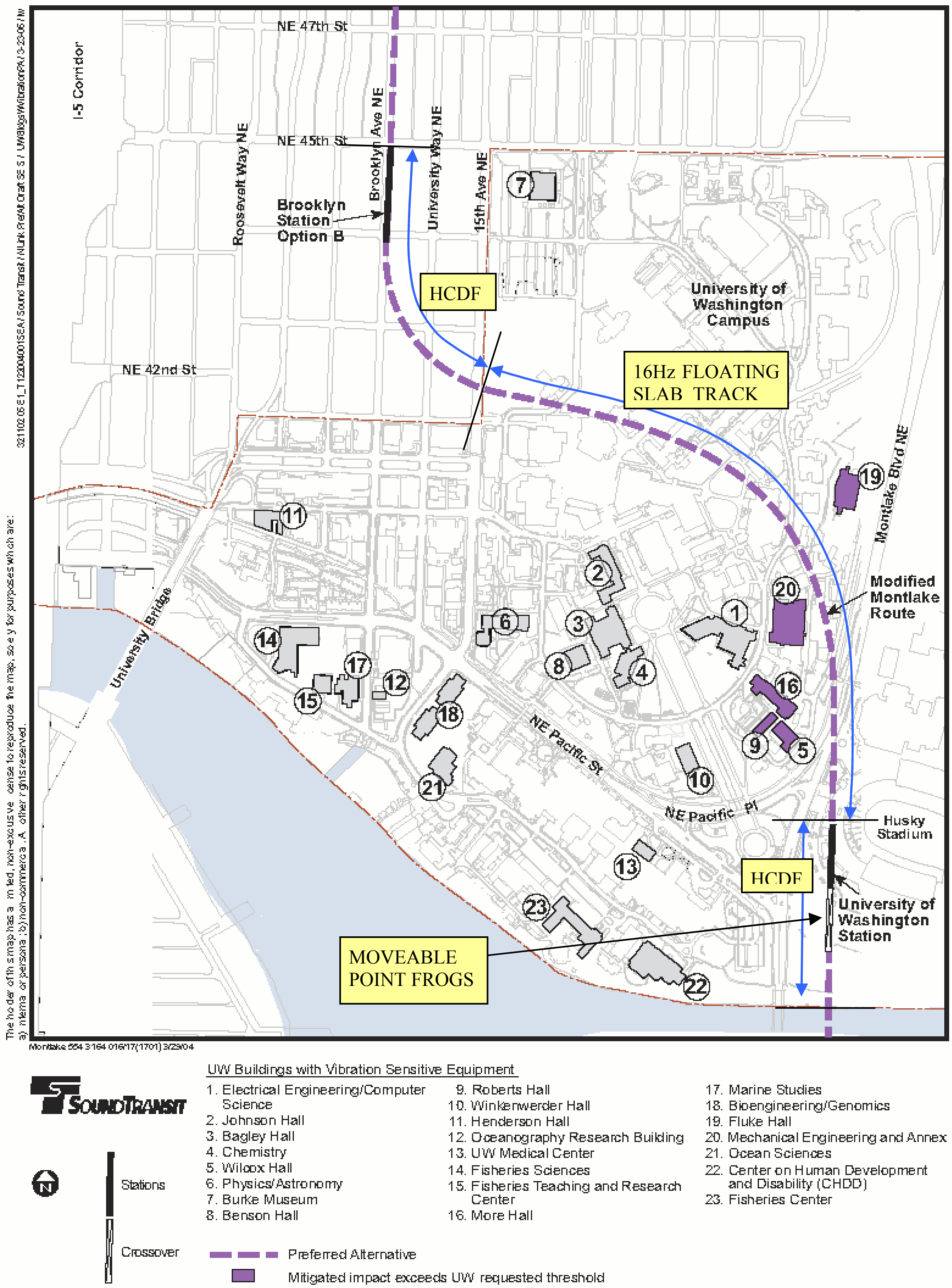

Figure 2 **Potentially Impacted Buildings - Vibration Analysis with Mitigation**

7 MONITORING SYSTEM

Development of a vibration monitoring system is also discussed for purpose of evaluating both pre-revenue conditions and performance during long-term operations. Vibration measurements would be necessary at locations within the subway tunnel and in various building locations on campus. The monitoring system could be used to establish performance criteria and manage facility inspection and maintenance activities over the long-term. The system could be designed to transmit measured vibration levels continuously or intermittently and regular reports would benefit both Sound Transit and the University research community. For these purposes, ground vibration from passing trains should be determined as the maximum root-mean-square vibration velocity measured with an averaging time equal to the time required for the train to pass the point of closest approach to the receiver.

8 CONCLUSION

A summary of the predicted vibration impacts at twenty-three buildings identified by the UW as vibration sensitive is provided in Table 1. Without mitigation, predicted vibration levels at fifteen of the twenty-three buildings during train passage exceed the UW Thresholds. With the proposed vibration control provisions, the predictions exceed the UW Thresholds at five of the twenty-three buildings listed. However, the predicted vibration levels are reduced substantially with the proposed mitigation.

Further testing of the ST vehicles is necessary to determine the level of vibration that would actually be produced. ST's first opportunity to test the vehicle will be during late 2006 or in 2007, and the results can be incorporated into the final design. Low frequency vibration will also be controlled by rail roughness and undulation amplitude, and further investigation of rail straightness is also recommended.

A substantial benefit of installing the floating slab track as vibration control mitigation would be very effective control of ground-borne noise in buildings located close to the tunnel.

Table 1 Comparison of Predicted Exterior Ground Surface Vibration Velocity Levels with UW Threshold for Two Trains

Building	Tunnel Depth (Ft)	Horizontal Distance (Ft)	Exceed UW Threshold Without Mitigation	Exceed UW Threshold With Mitigation
1) New Electrical Engineering	147	338	Yes	No
2) Johnson Hall	132	677	Yes	No
3) Bagley Hall	138	978	Yes	No
4) New Chemistry	125	1,008	Yes	No
5) Wilcox Hall	99	110	Yes	Yes
6) Physics/Astronomy	121	1,201	Yes	No
7) Burke Museum	78	826	Yes	No
8) Benson Hall	134	1,269	Yes	No
9) Roberts Hall	113	255	Yes	Yes
10) Winkenwerder Hall	102	683	Yes	No
11) Henderson Hall	58	1,208	No	No
12) Oceanographic Research	80	1,833	No	No
13) UW Medical Center	108	910	Yes	No
14) Fisheries Sciences	68	1,640	No	No
15) Fisheries Teaching Center	73	1,858	No	No
16) More Hall	113	137	Yes	Yes
17) Marine Studies	70	1,799	No	No
18) Bioengineering/ Genomics	100	1,612	No	No
19) Fluke Hall	140	333	Yes	Yes
20) Mechanical Engineering and ME Annex	124	9	Yes	Yes
21) Ocean Sciences*	104	2,056	No	No
22) CHDD	107	753	Yes	No
23) Fisheries Center*	100	1,242	No	No

* Background not available, but based on background at other buildings