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Potential low frequency ground vibration (<6.3 Hz) impacts from underground LRT operations

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Abstract

Vibration sensitive research activities at the laboratories of the University of Washington (UW) Physics and Astronomy Building (PAB) were a critical issue for the design of the Sound Transit Link Light Rail LRT system in Seattle, Washington. A study was conducted to measure and predict low frequency ground vibration generated by the LRT operations. The University's concern was an on-going research experiment in gravity, which had sensitivity to vibration below 6.3 Hz. The experiment was located on an independent concrete slab in an area cut-out from the building foundation with no connection to the building structure. Another concern was the planned future construction of a Life Sciences Center with vibration sensitive test equipment. This paper presents the results of a study to estimate the ground displacement at these buildings using empirical measured data of a similar deep tunnel transit system and finite difference modelling analysis.

1. Introduction

University of Washington (UW) research scientists are concerned about the potential vibration impact of trains operating along the underground section of the Link Light Rail alignment on sensitive equipment and experiments at the Physics Astronomy Building (PAB) and the proposed Life Sciences III Building. The center of these facilities is located approximately 128.0 m and 27.4 m from the centerline of the alignment, respectively, as shown in Fig. 1.

The proposed LRT alignment consists of two running tunnels and the Pacific Street Station with track centers spaced 27.4 m apart as shown in Fig. 2. Adjacent to the PAB, the Pacific Street Station and the two tunnels are 53.3 m below the ground surface. At the Life Science III Building, the two tunnels are 45.7 m below the ground surface. The tunnels are 6.4 m in outside diameter

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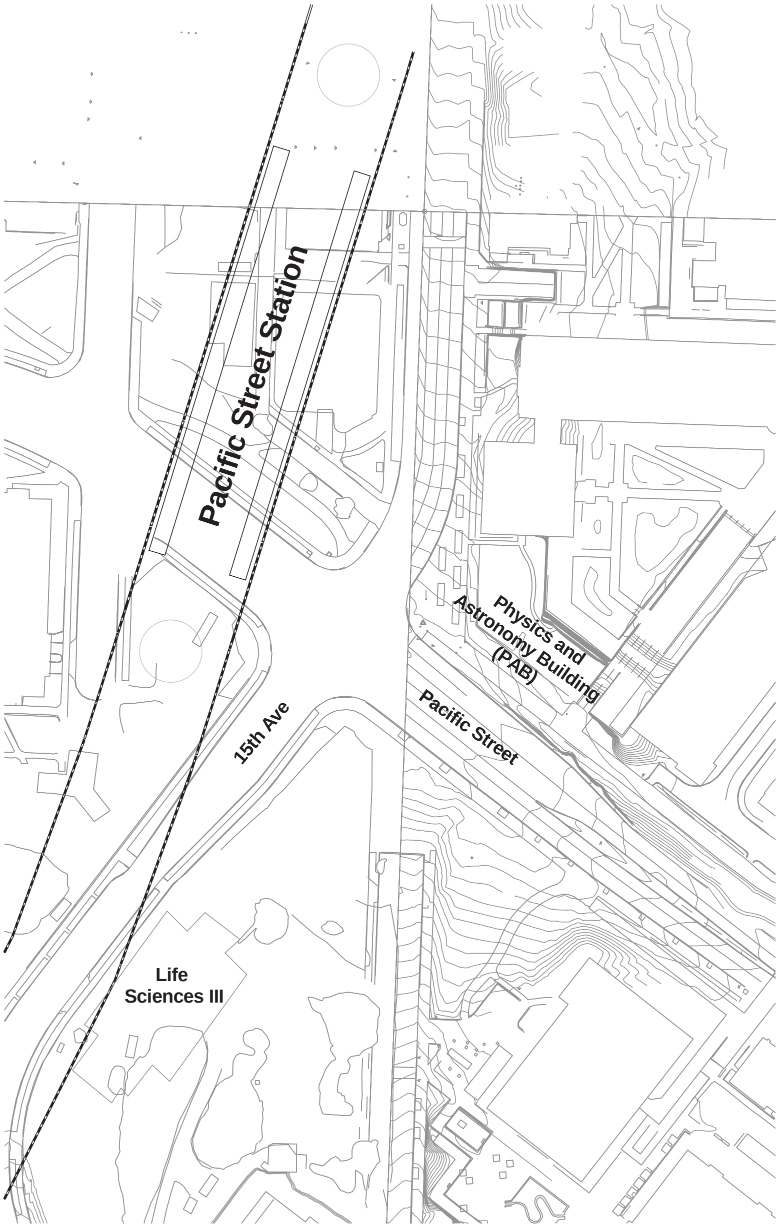

Fig. 1. Site map of Link Light Rail alignment.

and have a nominal 25.4 cm-thick concrete liner with an invert thickness of about 122 cm. The station platform tunnels are elliptical in shape have an outside diameter of approximately 11.3 m. The station platform tunnels include a utility chamber through the station invert.

The laboratory of greatest concern is where Professor Paul Boynton conducts experiments in gravity using a pendulum suspended from a fiber optic cable. His experiment is on a ‘‘seismic pier’’, a concrete base that sits on top of undisturbed soil, located meters 3.0 m below the building

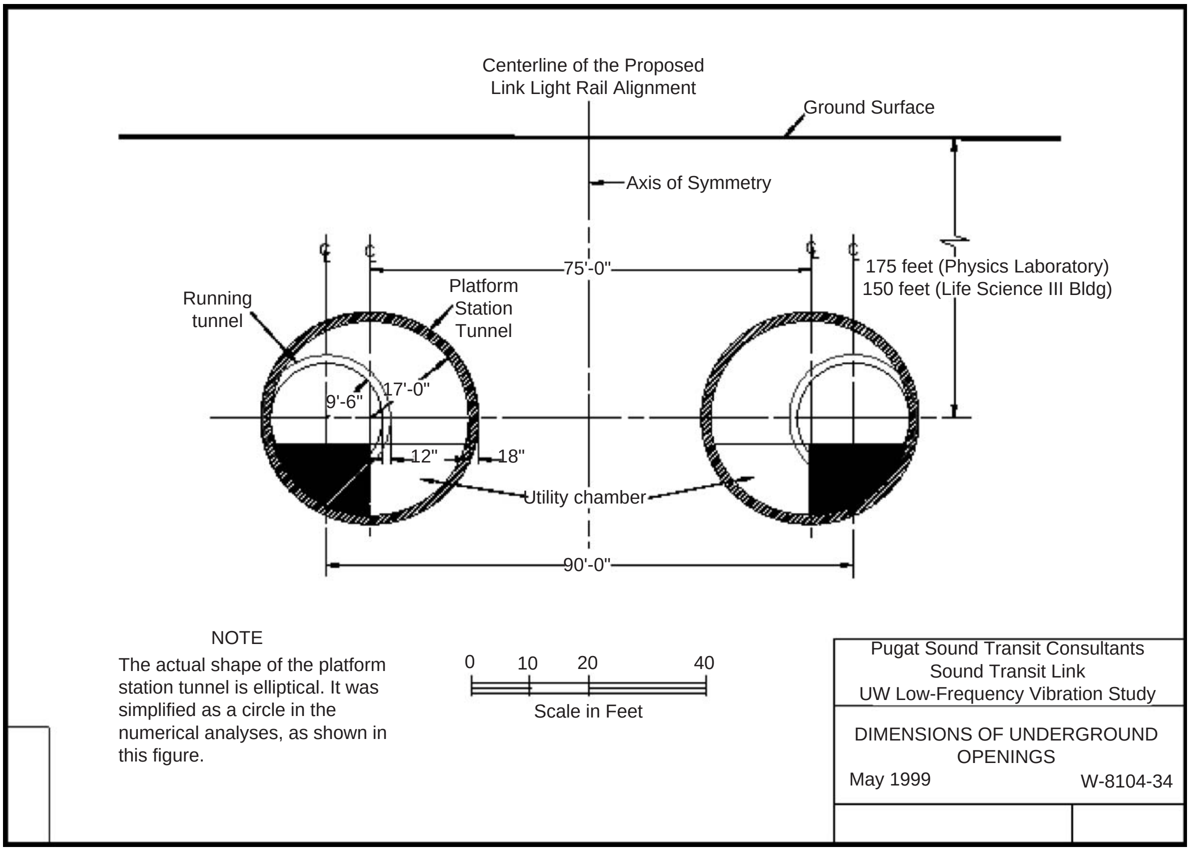

Fig. 2. Underground LRT tunnels.

foundation slab in an excavated area that has no physical contact with the building structure. Professor Boynton conducts his experiments in the evening and night-time because of the lower ambient ground vibration levels during these hours. His current concern is the vibration generated by bus traffic on Pacific Street that he has detected during his experiments, and his other concern is the future operations of the LRT.

In response to these concerns, Sound Transit initiated a study that was designed to determine the level of ground vibration on Professor Boynton's "seismic pier" from both future underground transit operations and from the existing bus movements on Pacific Street. The approach to this study was to use empirical measurements on a similar underground light rail transit system in order to validate a finite element model, and also to compare the forced vibration levels generated by local Seattle bus movements in close proximity to UW PAB with the proposed Link Light Rail LRT [1,2]. The elements of the study consisted of:

- Ground vibration measurements of the Tri-Met LRT vehicle operating in a subway section of the MAX Westside in Portland, Oregon. Portland was selected for these measurements because the Tri-Met vehicle (a Siemens Low Floor Car) is similar to the vehicle that will be used for Sound Transit and the geology of the Portland Westside Tunnel is similar to the soil stiffness at the UW.

- Ground vibration measurements of Metro buses operating on 15th Avenue and Pacific Street. These measurements were taken to determine if the bus movements were detectable.
- Finite difference analysis using the results of the measured ground vibration data and the geotechnical data to construct a mathematical model of the tunnel, PAB and Life Science Buildings. A numerical model of the Portland tunnel and soil geology was constructed and the modelling results were compared with the measured ground vibration levels at the surface. The model was then adjusted to account for the difference in soil conditions and distance to the tunnel at the UW site.

Since it is not possible to include all the data, either measured or modelled, within the limits of this paper, examples of the measured data along with the results and conclusions of the study are presented.

2. Ground vibration measurements—Tri-Met LRT vehicle

The UW Geophysics Department, using two CMG40T seismographs, conducted the LRT ground vibration measurements above the Tri-Met Westside Tunnel in Portland and bus ground vibration measurements in Seattle [3]. Simultaneous measurements were conducted within the tunnel structure, on the safety walk bench and at the surface above the tunnel. Three locations were selected along the tunnel to the west of the Washington Park Station: cross passage 4, at an invert depth of approximately 61.0 m; cross passage 3 a deeper invert location approximately 243.8 m to the east; and cross passage 5, a shallower invert depth, approximately 243.8 m to the west.

The in-tunnel and surface measurements were conducted during the night-time revenue hours beginning at 10 p.m. and extending into non-revenue hours using a test train. The speed of the revenue trains at all three cross passages was 89 kilometers per hour (km/h). To determine the varying ground vibration levels from different LRT operating conditions, train operators were instructed to adjust their speed when they entered the tunnel so they could pass the measurement location at speeds of 40, 56, 72, and 89 km/h. To simulate trains entering and leaving a station, the operators were instructed to stop at the cross passage, pause and then accelerate to 89 km/h. An example of the measurements is shown in Fig. 3 above cross passage 4, which presents the measured average vibration velocity (r.m.s.) of six trains plotted with the average of six background periods when there were no strong signals from other vibration sources. There are prominent background noise spikes at 14.4 and 21.8 Hz. The spectra indicate that vibrations from the trains in this frequency band are less than vibration levels from other sources (background noise).

3. Ground vibration measurements—Seattle metro bus

Vibration measurements were conducted at the PAB using seismometers at two sites: outside the building setback on Pacific Street, 9.1 m from the edge of the street; and inside the building on the “seismic pier” in Professor Boynton’s Laboratory. A Metro articulated bus, 13.4 m long, was

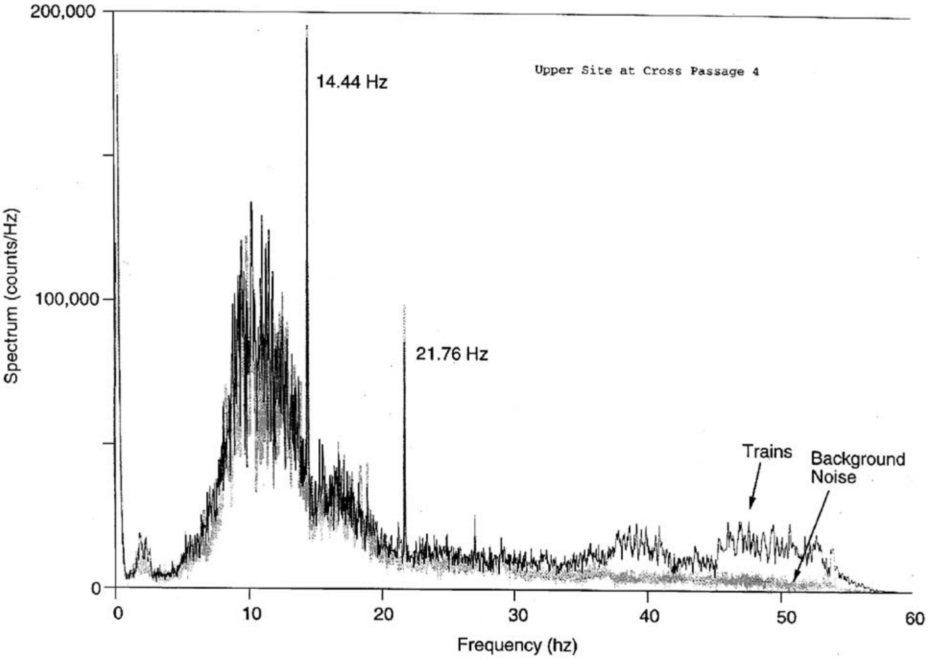

Fig. 3. Tri-Met train measurements at cross passage 4.

used as the source of vibration. The bus moved in a continuous loop along Pacific Street passing in front of the PAB and then returning to Pacific Street by 15th Avenue.

Fig. 4 shows a comparison of the measured signals at the outside and inside of the PAB. The buses are either marginally detectable or not detectable at all on the inside of the PAB.

Spectra of a typical bus signal measured on the ‘seismic pier’ are presented in Fig. 5. A comparison of the background vibration level, also referred to by seismologists as background noise, inside and outside the physics building indicate little difference between the two sites at frequencies below 15 Hz. From 15 to 25 Hz, the background noise outside the building is slightly higher.

4. Summary of measured data

Background vibrations in Portland and Seattle were very similar above 8 Hz. Below 8 Hz the background vibrations inside the Physics building were significantly higher. Signals from nearby buses were significantly higher than background levels at all sites except inside the Physics building. In Portland, trains passing through the tunnels could be detected above the background levels only between 1.5 and 2.5 Hz and between 35 and 55 Hz.

The upper frequency limit of the seismometers is 55 Hz. Signals even at these frequencies were only obvious for the faster trains. No obvious signals were detected from the slower trains and the ‘stop and go’ trains.

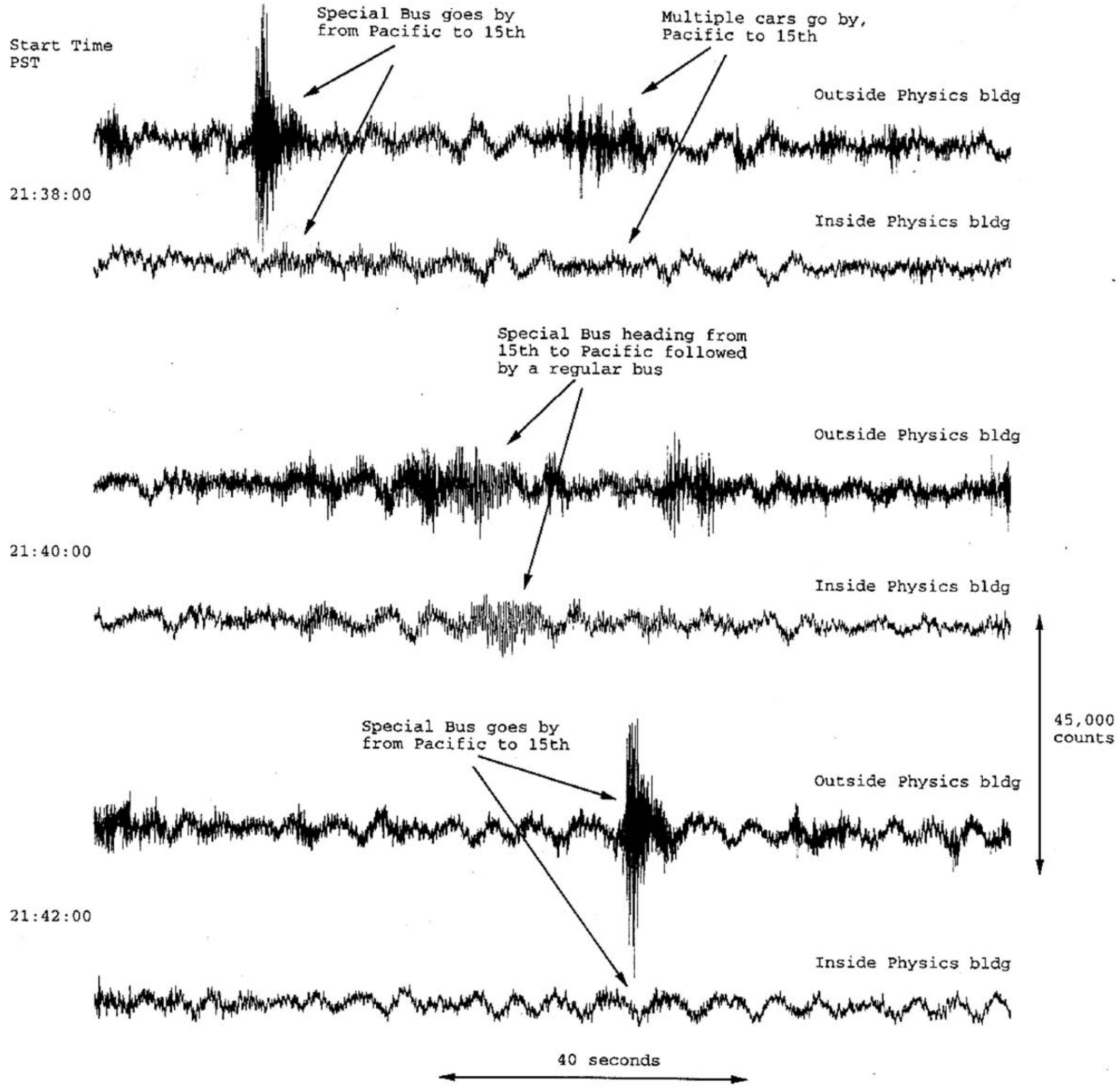

Fig. 4. Comparison of measured bus vibration inside and outside PAB.

The vibration levels generated by the Seattle buses were clearly detectable outside the Physics building, close to Pacific Avenue, but only slightly or not at all detectable inside the building located much further from Pacific Avenue. Background vibrations at the Physics building (both inside and out) have larger amplitude by a factor of 25 in the low frequency range (0.1–5.0 Hz) than in Portland.

Based on the results of these measurements, the following conclusions were drawn:

- The Metro bus pass-bys on Pacific Street were not detected on the seismic pier in Professor Boynton's Laboratory.

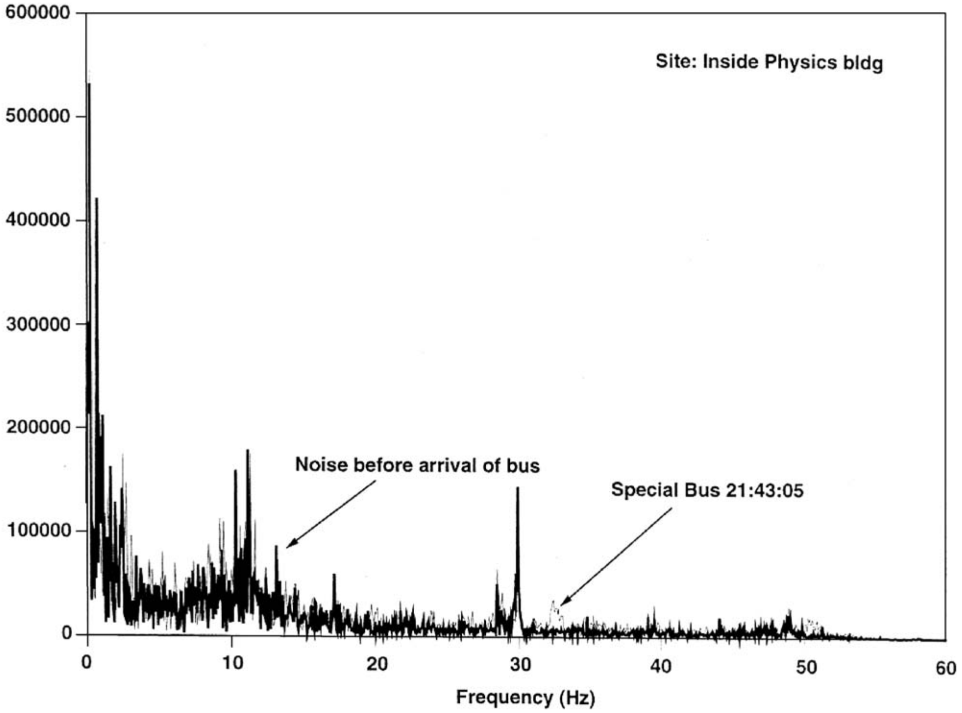

Fig. 5. Spectra of bus pass-by inside PAB.

- The measured background vibration level at the UW Physics Building is higher than the background in Portland at frequencies of 12.5 Hz and below.
- Tri-Met trains at 89 km/h were detected in Portland above the background vibration level at 1.5 to 2.5 Hz and 35 to 55 Hz.
- Train pass-bys at 72 km/h or slower were not detected above the background level.
- Stop and go train operations, to simulate entering and leaving a station, were not detected above the background level.

As shown by the measured data, the background noise levels are very similar above 8 Hz at the Portland site and at the special instrument pier in the basement of the UW physics building in Professor Boynton's laboratory. Below 8 Hz, however, background vibration levels at the physics instrument pier are significantly higher than at the Portland cross passage 4. Therefore, if we were to assume that train signals at UW and Portland would be similar, it is unlikely that trains at UW would be recorded in the Physics lab at low frequencies because of the high background noise there.

5. Finite difference analysis

The objective of the finite difference analysis is to estimate displacements beneath Professor Boynton's Laboratory in the PAB. Static loading was assumed to approximate the low frequency vibration due to train passage. To estimate displacements more precisely, numerical analyses of static displacements were conducted using the finite difference program FLAC3D.

Numerical analyses using FLAC3D were performed to predict displacements due to train loads at Tri-Met and bus loads at the UW site. The measured train vibrations at the ground surface of the Westside LRT Tunnel (Tri-Met) in Portland, and the measured bus vibrations inside the Physics Laboratory on the UW campus were used to validate the finite element model. The ratio between measured displacement and predicted displacement was designated as a Calibration Factor (CF). The analysis suggested that the CFs for the train case were more appropriate than CFs for the bus case. (The latter suggests that there is no influence of the bus and that only background noise is being measured.)

Three measures were evaluated to reduce displacements at the ground surface: filling the utility chamber in the station platform tunnel with concrete; increasing the stiffness of the running tunnel and station platform tunnel invert; and constructing a concrete slurry wall along the station, between the station and the Physics Laboratory.

5.1. Model descriptions

Two models were generated to simulate loading, geology, topography, and boundary conditions at the UW. One model was developed for conditions at the Physics Laboratory and another model was developed for conditions at the proposed Life Sciences III Building. A single model at the Physics Laboratory was generated for calibration of the bus loading. The train and bus loads were modelled as concentrated forces applied at appropriate nodes of the FLAC3D model. Since the applied loads are small with respect to the ultimate strength of the subsurface materials, a purely elastic constitutive model was used to represent the stress–strain relationship of the soils. Furthermore, since small elastic displacements are not influenced by the state of stress in the medium, only the change in stress was considered in these models.

The tunnel geometry, applied loads, general topography, and subsurface conditions at the two UW sites were determined to be sufficiently uniform to warrant the use of a half mesh to simplify the computational efforts. A sample perspective view of the train model is presented in Fig. 6.

As part of the Link subsurface exploration program, deep borings were drilled along the proposed alignment. The boring results indicate that the subsurface profile can be divided into three homogenous, isotropic layers as presented in Table 1. This table also presents the assumed material properties for the tunnel and pavement structures included in the various models.

The station liner was modelled with an opening to simulate the utility chamber shown in Fig. 2. For the bus case, it was assumed that the pavement along Pacific Street consists of 10.2 cm of asphalt concrete over 20.3 cm of base rock.

5.2. Model calibration

LRT vibration measurements obtained at the Tri-Met tunnel in Portland, Oregon and bus vibration measurements obtained inside the Physics Laboratory on the UW campus were used to calibrate the numerical models. Specifically, the results of the field measurements were used to establish calibration factors between measured and predicted displacements obtained from the FLAC model, which then were used to predict displacements due to future light rail train loading

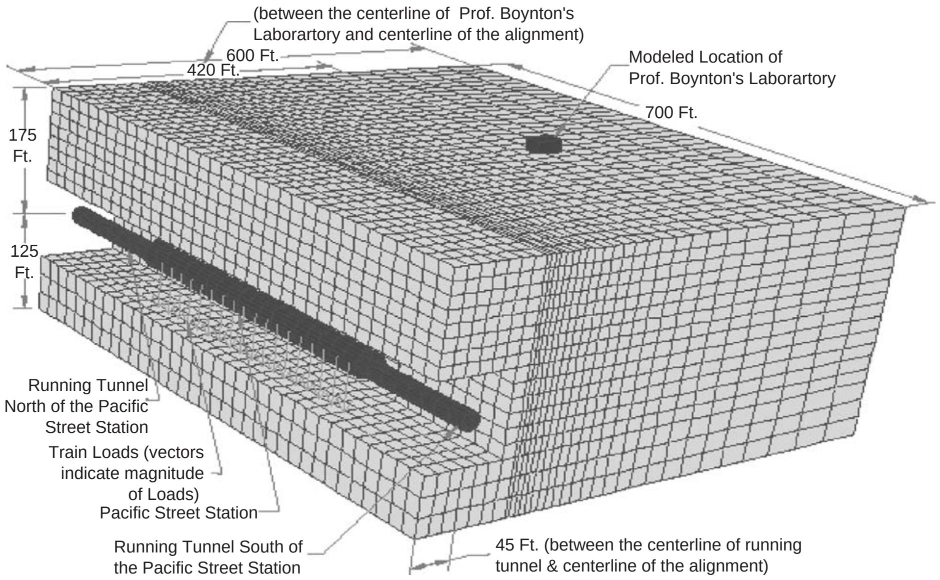

Fig. 6. FLAC3D mesh for analysis of vibration impact on Professor Boynton's Laboratory in PAB.

Table 1
Soil/structural units and shear moduli used in models

Soil/structural units	Depth (m)		Shear modulus (kg/cm^2)		
	From	To	Minimum	Average	Maximum
Fill	0	3.0	67	176	281
Sandy soils	3.0	24.4	—	5273	—
Clayey soils	24.4	91.4	2461	3515	4921
Pavement	Surface		—	4218	—
Concrete liner	Varies		—	105,460	—

at the Physics Laboratory. A FLAC model was constructed of the Tri-Met tunnel and surrounding geology and material properties.

The test train used in the field measurements at the Portland Tri-Met site consisted of two cars, with each car weighing 40,000 kg and being 27.4 m long. The measured displacement at the ground surface above cross passage 4 was 6.1×10^{-5} cm at 0.5 Hz. Based on the results of the measured data it is assumed that at 0.5 Hz, the displacement is due to the ambient vibrations. As such, the measured displacement solely from train loading would be less than or equal to 6.1×10^{-5} cm.

Numerical analyses were performed to predict the static displacements at the Tri-Met tunnel due to one-train passage for the subsurface conditions presented above. The measured displacement and predicted ground surface displacements at the centerline of the alignment is 5.2×10^{-5} cm, which when divided into the measured displacement results in a calibration factor (CF) of 1.2.

5.3. Physics laboratory, UW campus

Measured displacements inside the Physics Laboratory, due to a bus passage were also evaluated as part of calibrating the model. The bus used in vibration measurements reportedly weighed 22,500 kg and was 13.5 m long. The bus travelled on Pacific Street, approximately 64 m from the Physics Laboratory. The measured displacement inside the Physics Laboratory was 13.5×10^{-5} cm at 0.5 Hz. Like the Tri-Met case, the measured displacements include the bus-induced displacements and ambient vibrations. In other words, the actual bus-induced displacement is less than or equal to 13.5×10^{-5} cm.

Numerical analyses were performed to estimate displacements beneath the Physics Laboratory and the Life Sciences III Building on the UW campus. For the Physics Laboratory and the Life Sciences III Building, a full train load was assumed in each station and running tunnel, respectively, simultaneously. Each Link train was modelled as four cars, each 27.4 m long and weighing 67,000 kg.

Inspection of the results of the numerical analyses indicates that calculated ground surface displacements are not sensitive to the soil properties above the tunnel. Static displacements due to train loads will depend primarily on the material stiffness below the tunnel. The predicted ground displacements at the PAB and Life Sciences III Building are presented in Table 2.

5.4. Mitigation measures

As part of the numerical study of static displacements, three remedial measures were evaluated to reduce the ground displacement. The mitigation measures were:

1. Fill the utility chamber in the station platform tunnel with concrete (refer to Fig. 2).
2. Measure 1 plus increase the stiffness of the running tunnel and station platform tunnel invert to distribute the train loads over a larger area.
3. Construct a 0.6 m thick concrete slurry wall parallel to the station to increase the stiffness of the subsurface medium. The wall would be located 9.1 m horizontally from the northbound side of the station and would extend 13.7 m below the station invert.

Based on the results of the modelling of these three mitigation measures, none will reduce the displacements at the ground surface from the train vibrations.

Table 2
Predicted displacements—train case

Clayey soils shear modulus (kg/cm^2)	Displacement (cm)	
	Professor Boynton's Lab	Life Sciences Building III[a]
2460	5.3×10^{-5}	152×10^{-5} to 292×10^{-5}
3515	3.3×10^{-5}	102×10^{-5} to 203×10^{-5}
4921	2.3×10^{-5}	76×10^{-5} to 152×10^{-5}

[a] Range for each modulus represents spread over width of proposed building.

6. Conclusions

Based on the results of the vibration measurements and the finite difference analysis modelling, the following conclusions have been made:

- Based on the measured data of the Portland LRT operations, the expected low frequency (below 6.3 Hz) ground vibration levels from the operation of the Sound Transit LRT vehicles would not be detectable on the seismic pier of Professor Boynton's Laboratory or at any other location within the PAB. This is based on a maximum operating speed of 72 km/h in this segment of the underground alignment. Higher speeds of 89 km/h will be attainable at other locations along the alignment but due to the trackwork geometry on both sides of the Pacific Street Station, 72 km/h would be the highest speed before a train would need to decelerate into the next station.
- At Professor Boynton's Laboratory, the finite difference analysis projects a ground displacement in the range of 0.48×10^{-5} to 13.2×10^{-5} cm. This assumes the worst case of two fully loaded trains simultaneously passing the PAB. This would be lower than the ambient vibration level, 13.4×10^{-5} cm (0.1–1.5 Hz range) measured on the seismic pier of Professor Boynton's Laboratory. The ambient measurement was made at approximately 21.30 h when traffic and other outdoor activities are at a minimum. Ambient vibration levels during daytime hours are expected to be higher.
- At the Life Sciences III Building, the finite difference analysis projects a ground displacement in the range of 15.8×10^{-5} to 726×10^{-5} cm. These levels would be higher than the ambient level, 13.4×10^{-5} cm (0.1–1.5 Hz range) measured on the seismic pier of Professor Boynton's Laboratory, which is assumed to be the same for the basement of the Life Sciences III Building. However, if the predominate activities in the Life Science III Building are during daytime hours, further analysis of the ambient measurements made by Malone and Qamar [3] would be required to determine whether the low frequency effects of train operations would be detectable in this building.
- The results of the finite difference analysis demonstrates that over distance, the level of low frequency displacement is attenuated to the point where at 152 m or more from the centerline of the alignment, it is substantially lower than the measured ambient.

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