14 Aug 2008, 4:30pm - 6:00pm

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Recommended Citation

Tajirian, Frederick; Tabatabaie, Mansour; Asiri, Fred; and Seryi, Andrei, "Calibration of Computer Program Sassi for Vibration Transmissibility Analysis in Underground Structures Using Field Measured Data" (2008). *International Conference on Case Histories in Geotechnical Engineering*. 2.
https://scholarsmine.mst.edu/icchge/6icchge/session04/2

CALIBRATION OF COMPUTER PROGRAM SASSI FOR VIBRATION TRANSMISSIBILITY ANALYSIS IN UNDERGROUND STRUCTURES USING FIELD MEASURED DATA

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ABSTRACT

The successful operation of facilities that incorporate long electron-positron beams necessitates a very low vibration environment at the beam supports. Mitigation of the ground motion and imported vibration from the numerous vibrations sources is the main engineering challenge for these projects. Computer program SASSI was selected as an analysis tool for calculating the vibrations in underground tunnels resulting from near field sources due to equipment operation as well as far-field sources for a new generation of linear colliders. The program capabilities were validated by comparing calculated vibration results with field obtained measurements performed at the Los Angeles County Metropolitan Authority (MTA) Metro Red Line tunnels which consist of twin circular parallel tunnels that run through Miocene sandstone and shale. A 3D SSI model of a representative segment of the tunnels was developed. Analyses for three loading cases were performed simulating three tests that were done to characterize the transmission of vibrations from grade to a tunnel, 90 feet deep, transmission of vibrations inside one of the tunnels, and transmission of vibrations from one tunnel to the other tunnel. The maximum velocities, mobility functions, and displacement functions were calculated for each test case. The results were compared with available recorded data. Excellent agreement between SASSI results and recorded data for all three tests was obtained.

INTRODUCTION

This paper presents the results of soil-structure interaction (SSI) analysis of a segment of the Los Angeles twin MTA Metro tunnels. The response of the tunnels to forced vibrations was calculated. The segment of the tunnel that was modeled was the location where transmissibility measurements were previously made (GEOVision 2004).

The SSI analyses were performed using the computer program MTR/SASSI (Lysmer et al. 1981, Tabatabaie 1982, Tajirian 1981 and Tajirian and Tabatabaie 1985). This program is capable of modeling transmission of vibrations from one foundation (tunnel) to another foundation (tunnel) through the soil including foundation (tunnel) flexibility, radiation damping and embedment effects. SASSI is able to perform analysis due to forced vibration input resulting from equipment vibrations and wind, as well as seismic and ambient ground vibrations.

The results of the comparison demonstrate that the computer program SASSI can be used as a tool to model underground structures such as the International Linear Collider (ILC 2007) tunnels for managing the vibration budget, for optimizing the design of equipment supports in order to minimize the transmission or amplification of vibrations, and to calculate impact of existing background vibration sources such as traffic, construction and quarrying activities and other conditions on successful operation of vibration sensitive structures. Recorded vibration measurements taken in the MTA tunnel are compared with calculated results for three different loading scenarios.

DESCRIPTION OF TUNNEL STRUCTURE

The MTA Metro Red Line Tunnels consist of two parallel bores. The tunnels are circular with an approximate diameter of 20 feet. The bases of the tunnels are approximately 90 feet below grade. The distance between the centers of the two tunnels is approximately 40 feet. The tunnel segment that was analyzed is lined with precast concrete segments that are 9 inches thick. Additionally, the base of the tunnel includes a cast in place concrete invert supporting the rails plus a walkway. A typical cross-section is shown in Fig. 1.

SUBSURFACE SOIL/ROCK PROPERTIES

The subsurface soil/rock profiles and properties for SASSI analyses were developed from the available boring logs, sonic logs and laboratory test results. Because of the large observed variation in reported soil properties, two idealized soil profiles consisting of a lower (LB) and upper bound (UB) profiles were developed for the SASSI analyses.

The boring logs indicate that a thick layer of soil deposit overlying rock formation underlies the test site. The top soil layer is estimated to be about 20 feet thick and consists primarily of a thick layer of alluvium deposit. The water table is reported at approximately 12 feet below ground surface. The top soil layer is underlain by a rock formation called the Upper Topanga Formation. The properties used in the analysis are summarized in Table 1. Where ranges are defined, the lower value was assigned to the top of the layer, and the higher value was assigned to the bottom of the layer and values in between were obtained from linear interpolation.

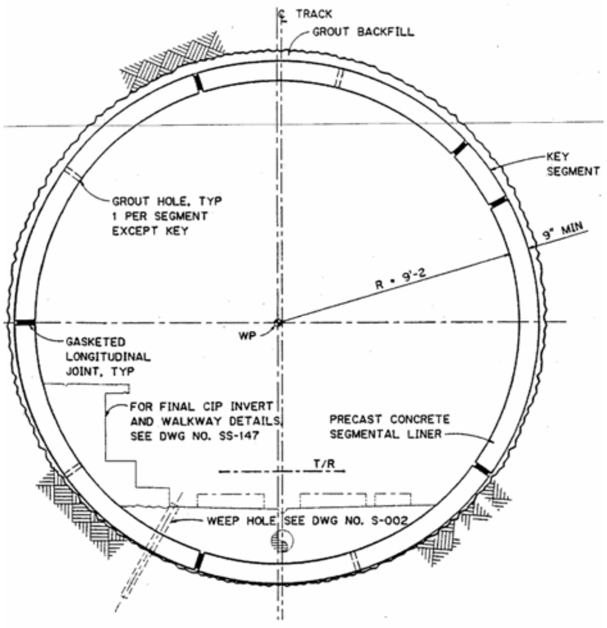

Fig. 1. Typical Tunnel Section.

Table 1. Site Properties

	Density (PCF)	Poison's Ratio	Shear Wave Velocity (fps)	
			LB	UB
Top Soil Layer 0-12 ft	120	0.33	650-690	850-895
Top Soil Layer 12-20 ft	120	0.47-0.49	690-850	895-1,050
Upper Topanga 20-180 ft	130	0.35	3,000	3,800
Upper Topanga 180-200 ft	130	0.35	3,000-6,730	3,800-8,650
Upper Topanga >200 ft	140	0.35	6,730	8,650

SASSI MODEL

Tunnel Finite Element Model

Because the two parallel MTA tunnels are identical, advantage was taken of geometrical symmetry by modeling only one quarter of the total model to reduce the computational effort in SASSI. The symmetric and anti-symmetric solutions were obtained separately and then combined to obtain the exact solution of the total system (both tunnels). For this approach to work it is assumed that the two tunnels have the same dimensions and structural properties and the forcing function is located on the plane of geometrical symmetry. In the SASSI procedure, the site is modeled as a layered system over halfspace while the tunnel components are modeled using finite elements. Excavated rock is modeled with three-dimensional solid finite elements. The stiffness and mass of these elements are subtracted from the layered medium and result in a rectangular cavity that is 20 ft. by 20 ft. and 250 ft. long. The properties of the excavated rock elements are equal to the rock properties defined in Table 1 for LB and UB rock at a depth of 70 to 90 feet. A total of 800 cube elements with 5 ft. side dimensions are used. The element dimensions are selected to transmit waves up to 100 Hz. In order to model a circular excavation in the rock, the rectangular excavation described above is backfilled with rock solid elements. These elements have identical properties to the excavated rock elements. The addition of these elements will result in a cylindrical excavated body with a diameter of 20 ft. and a length of 250 ft. The concrete tunnel invert was modeled with 200 solid elements. The concrete tunnel liner was modeled with 800 four node flat plate elements. The liner was assumed to be 0.88 ft. thick. The concrete properties used are summarized in Table 2. The SASSI model is shown in Fig. 2 and Fig. 3. The figures show the two planes of symmetry that allowed modeling a ¼ of a single tunnel.

Table 2. Concrete Properties

Young's Modulus (psf)	5.2×10^8
Poisson's Ratio	0.17
Density (pcf)	150
Damping Ratio (%)	1.0

Input Force

Five different ambient and forced vibration tests were carried out by GEOVision. The purpose of these five test types was to gather different vibration transmission information into, along, between, and out of the twin tunnels. For the SASSI analyses described in this paper, information from the following three tests was used:

- GEOVision Test No. 2 – Controlled source at grade and measurement at grade and in Tunnel A.
- GEOVision Test No. 3 – Controlled source and measurements in Tunnel A.
- GEOVision Test No. 4 – Controlled source in Tunnel A and measurements in Tunnels A and B.

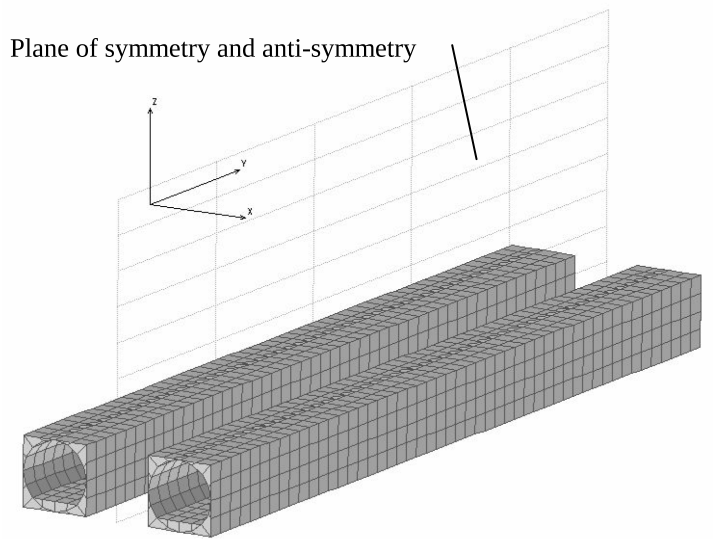

Fig. 2. SASSI Model, Showing 1st Plane of Symmetry

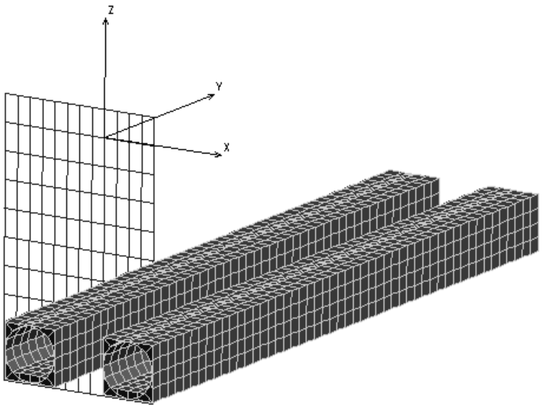

Fig. 3. SASSI Model, Showing 2nd Plane of Symmetry

ANALYSIS CASES AND RESULTS

The controlled vibration source consisted of a Bison Model EWG accelerated weight drop consisting of a steel weight of 220 lb (GEOVision 2004). The weight was accelerated by large rubber bands in tension. A 500-g piezoelectric accelerometer was fixed to the mass to directly measure the force impulse transmitted to the ground.

Test No. 2 Source at Grade

The purpose of Test 2 was to measure the transmission of vibrations from the ground surface to the tunnel. The weight drop was applied at the surface above Tunnel A. An array of sensors was placed in Tunnel A to measure the vibration response. A force time history was calculated by multiplying the measured acceleration by the hammer weight. The recorded force time history for Test No. 2 for ten weight drops is shown in Fig. 4 (Nigbor 2004a). The force time history associated with the seventh pulse, shown in Fig. 5 was applied to the SASSI model as shown in Fig. 6. Dynamic response was calculated at several nodes located at grade and along the length of Tunnel A.

Figure 7 compares the computed peak vertical velocities from SASSI for the lower bound and upper bound soil profiles with the recorded peak velocities. Note that at grade peak velocities were recorded at 20 ft. from the source and in Tunnel A at 0, 100, and 200 feet longitudinally from a point located directly below the source. It can be seen from Fig. 7 that there is excellent agreement between the computed and measured velocities at grade and good agreement in Tunnel A. The calculated velocities in the tunnel are about 40 percent higher when using the LB results. Figure 8 compares the calculated mobility for LB site with measured mobility at two points. The first point is located at grade 20 feet from the source and the second point is in Tunnel A 0 ft. from the source plane. The calculated and measured mobilities are in good agreement.

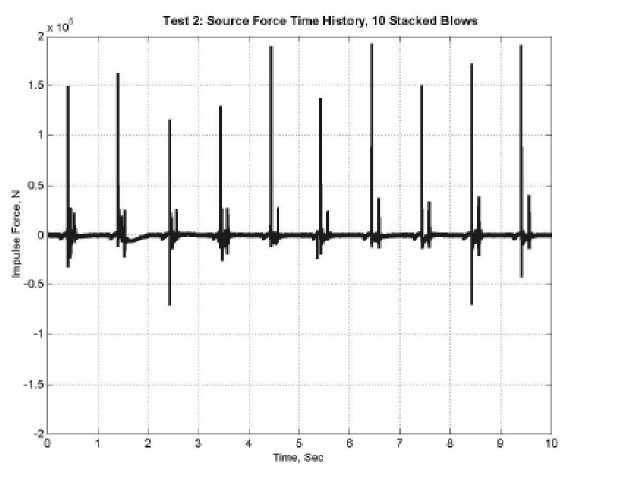

Fig. 4. Test 2 Recorded Force Time History for Ten Drops

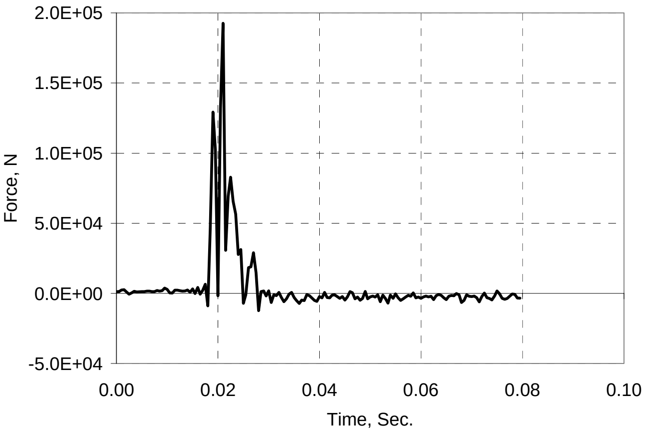

Fig. 5. Test 2 SASSI Input Force Time History

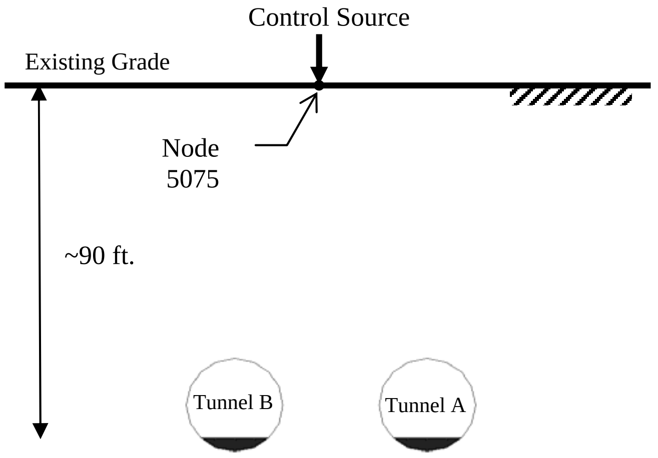

Fig. 6. Location of Input Force, Test 2

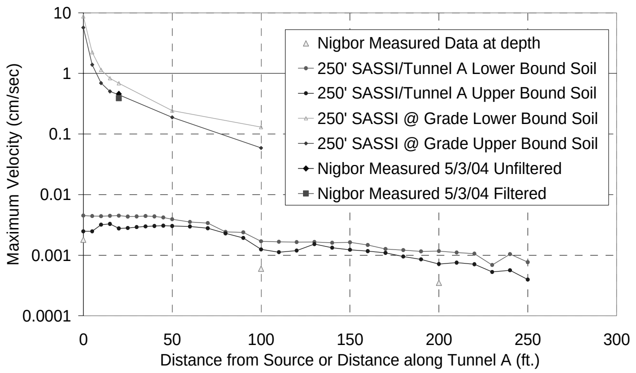

Fig. 7. Test 2 Comparison of Maximum Velocities

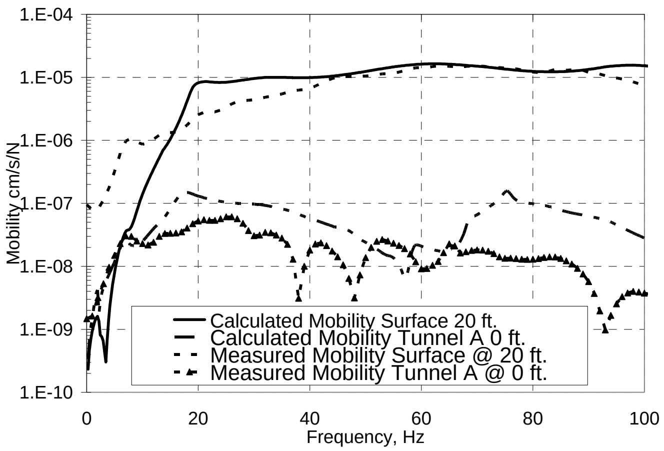

Fig. 8. Test 2 Comparison of Mobilities

Test No. 3 Source in Tunnel A

The purpose of Test 3 was to measure the transmission of vibrations along the tunnel. The weight drop source was mounted on the hitch receiver in Tunnel A and the vibrations were measured along the tunnel with an array of sensors. The hammer force was applied to the SASSI model at a point corresponding to the surface of the tunnel invert.

The dynamic response of Tunnel A was calculated in terms of peak vertical velocity, mobility functions, and displacement transfer functions. Figure 9 compares the peak vertical velocities for LB and UB soil profiles with recorded peak velocities. The calculated values at locations from 0 ft. to 250 ft. in Tunnel A are presented. Note that the recorded values from Test 3 and Test 4 are shown in Fig. 9. Both filtered and unfiltered velocities are included. In general there is good agreement between calculated and recorded values at all available points. Also note that the calculated results are not very sensitive to the soil properties used.

Test No. 4 Source in Tunnel B

The purpose of Test 4 was to measure the transmission of vibrations through the soil between Tunnel A and Tunnel B. For Test 4, the same hammer setup in Test 3 was used. The GEOVision report notes that the source accelerometer did not function during the tests, so no source force data was available. In the SASSI analysis, the same force used for Test 3 was also used for Test 4. The source was applied in Tunnel A, and the vibrations were measured along Tunnel A and Tunnel B with an array of sensors placed in each tunnel.

The dynamic response of Tunnel B due to source in Tunnel A was calculated in terms of peak vertical velocity, and mobility functions. Figure 10 compares the peak computed vertical velocities for LB and UB soil profiles with recorded peak velocities. The calculated values are presented at points in Tunnel B from 0 ft. to 250 ft., measuring from the vertical plane where the source is applied. There is good agreement between calculated and measured values.

Figure 11 compares the calculated mobilities equidistant from the source. The first curve is the mobility in Tunnel A, 40 ft. from the source. The second curve is the mobility in Tunnel B again 40 ft. from the source. Since the distance from the center of Tunnel A to the center of Tunnel B is 40 ft, this places the point at 0 ft. from the vertical plane perpendicular to the two tunnels and where the source is located. It can be seen from Fig. 10 that the two curves are almost identical which indicates that the vibration propagation inside Tunnel A is similar to the propagation from Tunnel A to Tunnel B. In this case the parameter governing the vibrations is the distance of travel from the source.

Figure 12 compares the peak calculated displacements along the length of Tunnel A and Tunnel B for tests 3 and 4. A similar observation as the one described in the paragraph above can be made regarding the effect of distance on the degree of attenuation. The peak displacement in Tunnel A forty feet from the source is equal to 3.52E-05 cm and the peak displacement in Tunnel B forty feet from the source is equal to 3.27E-05 cm.

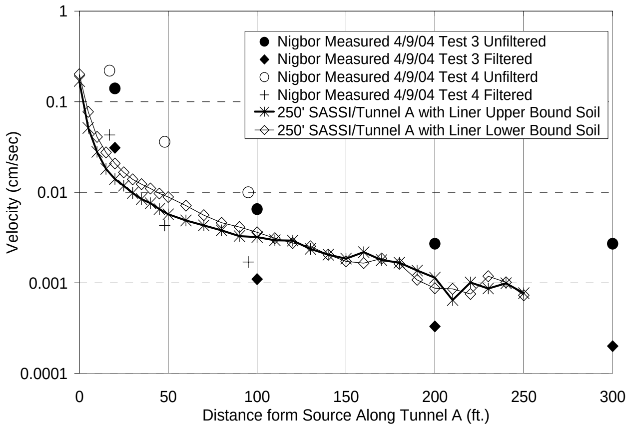

Fig. 9. Test 3 Comparison of Maximum Velocities

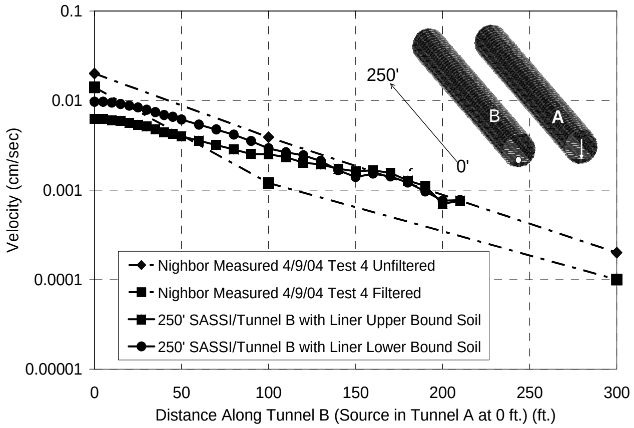

Fig. 10. Test 4 Comparison of Maximum Velocities

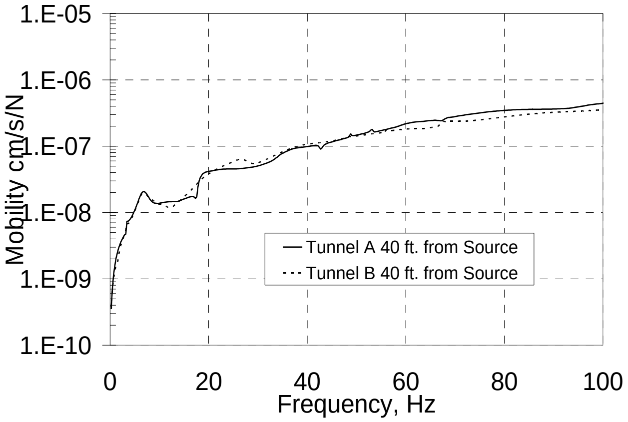

Fig. 11. Comparison of Calculated Equidistant Mobilities

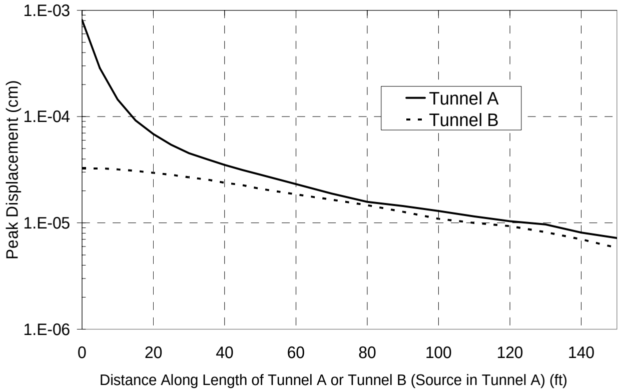

Fig. 12. Calculated Peak Displacements in Tunnel A (Test 3) and Tunnel B (Test 4)Lower Bound Soil

CONCLUSIONS

The computer program SASSI was used to compute the response of a segment of the Los Angeles twin MTA Metro tunnels to forced vibrations. The analyzed segment was the same location where transmissibility measurements were previously made. A three dimensional model was used to represent the tunnels. Existing soil boring data were reviewed and appropriate soil properties for the site were developed. Due to uncertainties and limitations in the available data, the analyses were performed using lower bound and upper bound properties. The lower bound soil boring data provided a better agreement with the analytical results and was used for many of the graphical comparisons.

The SASSI analyses were performed for three loading cases simulating three tests that were done to characterize the transmission of vibrations from grade to a tunnel, 90 feet deep, transmission of vibrations inside one of the tunnels, and transmission of vibrations from one tunnel to the other tunnel. The recorded forcing function (source) in these tests was used as the input forcing function in the SASSI analysis.

The maximum velocities, mobility functions, and displacement functions were calculated for each test case. The results were compared with available recorded data. Based on these comparisons the following conclusions can be made:

- The good comparison between SASSI results and recorded data for all three tests provides calibration of the 3D SASSI model. This was achieved without excessive refinement of the SASSI model.
- The SASSI computer program can be used to predict the attenuation of vibrations emanating from various sources in facilities that are sensitive to vibrations such as ones that incorporate long electron-positron beams. These facilities may be located near surface or deep underground.

- The calculated vibrations in Tunnel A and Tunnel B are similar at points equidistant from the vibration source indicating that attenuation magnitude is more strongly correlated with propagation distance than the other parameters which were represented in the model such as tunnel geometry and liner properties.

SASSI can be used as an effective tool to predict the vibration environment for various types of structures, including buildings, underground tunnels and pipes, various schemes used to isolate structures from vibration sources such as trenched, or columns supported on isolated foundations. The analysis can substantially minimize or even entirely eliminate the need for costly field testing. These predictions can be of a direct nature as well as comparative studies to determine the preferred design options. This approach would allow for better optimization of the design of equipment and supports which would result in better utilization of tight vibration budgets in vibration sensitive operations. Some examples include:

- The prediction of the attenuation of steady-state vibrations emanating from various rotating equipment and from other components generating vibrations such as flow-induced vibrations within facility piping systems.
- Various designs for equipment skids can be evaluated to minimize transmission of vibrations to parts of the facility that are vibration sensitive such as the beam tunnel of the ILC. SASSI can be used to perform comparative studies to optimize the design of the skids by stiffening the skids, adding concrete to increase the weight or the use of isolators or springs with an appropriate isolation frequency. Through this optimization it is possible to select the most cost effective skid design and/or isolation system without being dependent upon costly testing that may delay completion of the project.
- Predict the response from various piping which may be located in the facility or underground away from the facility. For ILC the Low Conductivity Water (LCW) supply pipes may result in unacceptable vibrations. The "Belvins" methodology can be used to determine the vibratory forcing functions, the pipe size, flow velocity, pipe support spacing, and pipe support isolation system, can be evaluated using the SASSI models. The SASSI models can be used to conduct parametric evaluations of the LCW pipeline configurations in order to develop an efficient pipeline design for the LCW system.
- The prediction of vibration attenuation emanating from sources located at grade above underground facilities such as the ILC tunnels. Vibrations produced by various service facilities that could be located on the ground surface as well as other extraneous vibration sources such as nearby train or vehicle traffic can be studied using the SASSI models. These studies can be used to characterize the vibration environment for any surface vibration sources applicable to the final site selection.

- The SASSI models can be used to establish the vibration environment produced from sources that may be identified in the future so that their vibratory effects can be accommodated in the final design of a facility. Similarly the impact of installation of future equipment after the facility is constructed can be evaluated.

SASSI can be used as a calculation tool for other geotechnical effects. For example the procedure described in this paper can be used to calculate the effects of vibration on settlement of foundations in non-cohesive soils. Ground velocities can be calculated due to various dynamic events to estimate the magnitude of settlement.

REFERENCES

GEOVision Geophysical Services [2004], "Tunnel Vibration Measurements Conducted at MTA Universal Subway Station North Hollywood, California," Report prepared for Parsons Pasadena, California, Report 3230-01 Rev 4.

International Linear Collider [2007], "What is ILC". http://www.linearcollider.org/cms/?pid=1000000.

Lysmer, J., M. Tabatabaie, F. Tajirian, S. Vahdani, and F. Ostadan [1981], "SASSI – A System for Analysis of Soil Structure Interaction," Report No. UCB/GT/81-02, Geotechnical Engineering, Department of Civil Engineering, University of California, Berkeley, April.

MTR/SASSI [2004], System for Analysis of Soil-Structure Interaction, Version 5.0, Volume I User's Manual.

Nigbor, R. [2004a], "Test2-timedomainpeaks.xls," Attachment to email dated May 3.

Nigbor, R. [2004b], "MTA-peaks-test3.xls," Attachment to email dated April 9.

Tabatabaie, M. [1982], "*The Flexible Volume Method for Dynamic Soil-Structure Interaction Analysis*." Ph.D. Dissertation, University of California, Berkeley.

Tabatabaie, M. [1996], "Analysis of Soil Structure Interaction Due to Ambient Vibration Proposed National Ignition Facility, Livermore California," A Report Prepared for Lawrence Livermore National Laboratory.

Tajirian, F. [1981], "*Impedance Matrices and Interpolation Techniques for 3-D Interaction Analysis by the Flexible Volume Method*." Ph. D. Dissertation, University of California, Berkeley.

Tajirian, F. and M. Tabatabaie [1985], "Vibration Analysis of Foundations on Layered Media," *ASCE Proceedings on Vibrations for Soils and Foundations*, Detroit, Michigan.