VIBRATION MODEL VALIDATION FOR LINEAR COLLIDER DETECTOR PLATFORMS*

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Abstract

The ILC and CLIC reference designs incorporate reinforced-concrete platforms underneath the detectors so that the two detectors can each be moved onto and off of the beamline in a Push-Pull configuration. These platforms could potentially amplify ground vibrations, which would reduce luminosity. In this paper we compare vibration models to experimental data on reinforced concrete structures, estimate the impact on luminosity, and summarize implications for the design of a reinforced concrete platform for the ILC or CLIC detectors.

BACKGROUND

Reinforced concrete platforms proposed for CLIC and ILC are quite thick and rigid to minimize amplification of ground motion and the adverse effects of platform resonant modes. Such a rigid structure may have stiffness comparable to the foundation or ground on which it rests. Vibrational modes of the platform will couple to the ground, and the ground may need to be included in the mechanical model.

The foundation or ground may be modeled using a commercial finite element analysis (FEA) program. However, this will generally require simulation of a large ground volume and will consume significant computing time and resources. A simplified "cone model" as described by Wolf [1] should generally be sufficient to capture the main features of soil-structure interaction.

SOIL-STRUCTURE INTERACTION MODEL

Basic Cone Model

The "cone model" envisions the platform as resting on a truncated cone of soil or ground material, as shown in Fig. 1. The cone aspect ratio for horizontal and torsional motion is different than for vertical translation and rocking motion; only vertical motions will be considered here. Assuming a platform with a circular base, the cone's aspect ratio z_0/r_0 is given by Eq. 1:

$$\frac{z_0}{r_0} = \frac{\pi}{2}\frac{(1-\nu)^2}{1-2\nu}, \nu \le \tfrac{1}{3} \quad \text{(compressible material)} \quad (1)$$
$$= \pi(1-\nu), \tfrac{1}{3} < \nu \le \tfrac{1}{2} \quad \text{(nearly incompressible)}$$

where:

ν is Poisson's ratio for the soil
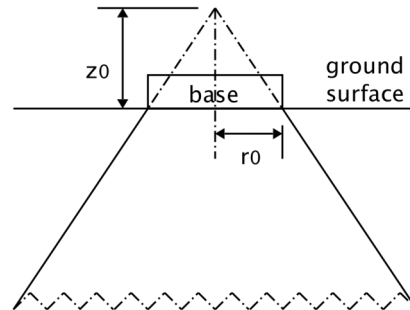z_0 is the height of the cone
r_0 is the radius of the base

Figure 1: Basic cone model for soil-structure interaction.

Vertical Translational Motion

For vertical translation, the cone of soil may be modeled by a simple spring (K) in parallel with a damper (C) [Fig. 2]. In the case of "nearly incompressible soil" an additional "trapped mass" of soil beneath the base of the platform must be included. Most material of interest at accelerator sites will be compressible; incompressible soil will not be considered further in this paper. Eq. 2 gives the values of K and C:

$$K = \frac{\rho c_p^2 A_0}{z_0}$$
$$C = \rho c_p A_0 \quad (2)$$

where:

A_0 is area of base
c_p is compressional wave velocity
ρ is soil density

Vertical Rocking Motion

Similarly, for vertical rocking motion of the base, the cone of soil may be modeled by a torsional spring (K_θ) in parallel with a torsional damper (C_θ). Eq. 3 gives the values of K_θ and C_θ:

$$K_\theta = \frac{3\rho c_p^2 A_0 r_0^2}{2z_0}$$
$$C_\theta = \frac{\rho c_p A_0 r_0^2}{2} \quad (3)$$

Typical Material Properties

The Poisson ratio ν for rock and soil can vary over a wide range of values, from 0.05 to 0.45 [2]. A value of

0.25 (the value for a "Poisson solid") is often used as an approximation for seismic studies. Typical properties for a few materials are shown in Table 1.
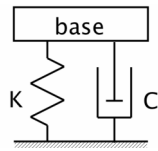

Figure 2: Simple spring-damper mechanical model.

Table 1: Properties of a Few Representative Materials

Material	ν	ρ (g/cc)	c_p (m/s)	z_0/r_0
Concrete	~0.2	~2.4	~3500	~$8\pi/15$
Generic rock	~0.25	~2.5	2k-7k	~$9\pi/16$
Carbonate rock	~0.3	~2.8	4k-7k; typ ~5k	~$\pi/3$
Sandstone	~0.2	~2.6	2k-5k; typ ~3k	~$8\pi/15$
Uncompacted sand	~0.33	~2.5	<3k	~$\pi/3$

Layered Materials

The previous discussion assumes homogenous soil material. If the ground is highly layered (e.g. a thick concrete floor on top of rock or soil), a more complex layered model is more appropriate [1]. However, if one material is dominant, a simple homogeneous model may still be adequate.

SLAC EX-6 BLOCK

Vibration measurements and simulations were done on a SLAC EX-6 reinforced concrete shielding block, which is 3 feet thick, 6 feet wide, and 24 feet long. An EX-6 block was placed on the floor of SLAC End Station A (ESA). The ESA floor is a 6" concrete slab on a thin layer of gravel on sandstone. The block was positioned on a kinematic support of three steel pads, each 3" x 6" x 1" thick (Fig. 3). Two steel pads were placed near the two corners at one end of the block, and the third pad was centered near the opposite end of the block.

Measurements

Vibration measurements were done with Sercel/Mark L4-C seismometers, low-noise preamplifiers, and a Labview data acquisition program. Various excitations were applied to the floor and to the block, including ambient motion, sharp impulses, and excitation via a variable-frequency motor with an offset mass. The resonant frequency of the fundamental bending mode was measured to be ~23 Hz.

When excited at this fundamental mode, the ends of the block (above the steel pads) showed significant vertical motion in phase with the motion of the center of the block. The end supported by a single pad moved 40-50% as much as the center, while the end supported by two

pads moved 20-25% as much as the center. The block interacts and couples strongly with the ground.

Figure 3: EX-6 block in SLAC End Station A.

Ground Model

Each 3" x 6" rectangular pad has about the same area as a disc with 2.5" radius. We assume that ground rigidity is dominated by sandstone, with c_p of ~2200 m/s (calculated [3] from recent measurements of shear wave velocity of ~720 m/s at SLAC SLD hall).

With this value of c_p and typical sandstone values from Table 1, the ground interaction may be modeled as a spring and damper under each pad with spring constant K of 6×10^8 N/m, and damping constant C of 1.1×10^4 Ns/m, per Eq. 2. In order to include torsional compliance, we modeled each spring as four separate springs each with K of 1.5×10^8 placed under each pad on a rectangular pattern of ~3.5" x ~5" [1, Table 2-2].

Simulations

Vibration simulations were done with ANSYS Workbench, using known material properties for SLAC concrete. Simulating the steel pads on fixed, rigid ground yielded a fundamental resonant frequency of the concrete block at ~35 Hz, with no motion of its ends. This is a poor match to measurements.

Adding the springs and dampers under each pad with values calculated above, the simulation yields a fundamental resonant frequency of ~22 Hz. The relative deflections at the ends and center of the block above the steel pads are about 20% and 40% of the deflection at the center of the block (Fig. 4). This simulation provides quite a good match to the measurements summarized above.

CERN CMS PLUG

The plug on the access shaft of the CERN CMS experiment is a reinforced concrete slab of 16 m x 20 m with a 2.2 m thickness. This plug covers the access shaft to provide shielding during machine operations. It has also been used as platform for the gantry large detector components (over 2000 tons) before lowering them

underground. This plug is similar in design to a Push-Pull detector platform.
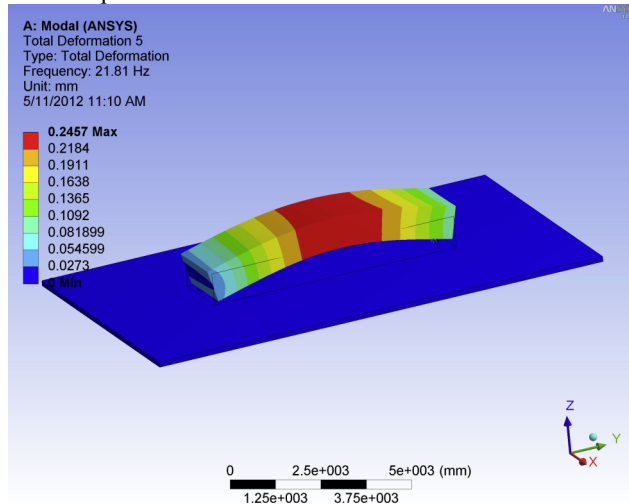

Figure 4: Simulated fundamental resonant mode of EX-6 block.

An ANSYS FEA model has been developed to simulate the static and dynamic behavior of the plug and to benchmark against a set of experimental dynamic measurements done previously. A full 3D model of the platform with iron rebar was used. The fundamental vibration mode was found to be 19 Hz, with maximal deflection at the center of the platform. This is very close to the 21 Hz fundamental mode measured experimentally.

A simplified finite model of the slab, with plate elements, has been developed to reduce the number of modes and the computation time for random vibration analysis. The modal analysis of the plate model was benchmarked against the 3D model, obtaining practically the same eigenfrequencies and eigenmodes.

Figure 5 shows the simulated vs. measured RMS displacement at the center of the slab, with the simplified model driven by ambient ground vibrations as measured by a reference geophone. Several values of damping were simulated. A damping ratio for concrete of 5-6.5% best matches both the measured Q of the fundamental mode and the measured RMS displacement, though 2% is more typical for concrete.

$$\sigma = \sqrt{\langle x^2 \rangle} = \sqrt{\int_{f_1}^{100\,Hz} P(f)\,df}$$
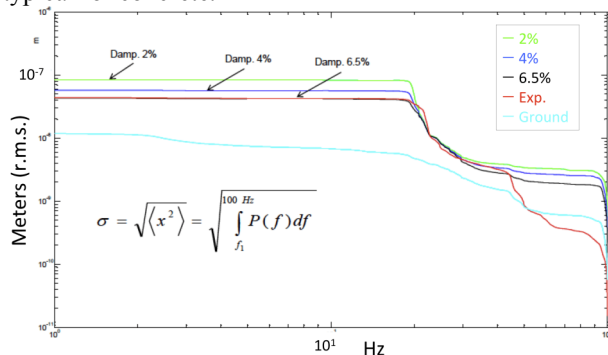
Figure 5: Simulations and measurements of integrated RMS vertical displacement at center of CMS plug.

We have not yet incorporated the cone model of ground interaction into this simulation. The perturbations should be smaller than seen on the EX-6 block, due to the larger contact area between the plug and the ground. Ground coupling should slightly lower the simulated fundamental resonant frequency and slightly increase its damping. This may explain why the measured damping of the fundamental mode is higher than expected.

IMPACT ON LUMINOSITY

Simulations have been done with Lucretia [4] to study the effect of ground motion on luminosity of the ILC BDS. The BDS design incorporates a split final focus doublet, with the QF1 magnet in the final focus tunnel and the QD0 magnet on the Push-Pull platform. This design also incorporates an intra-pulse feedback system. Simulations show that in order to limit luminosity loss to less than 1%, the pulse-to-pulse position jitter of the QD0 magnet must be less than 50 nm.

Simulations included an estimated transfer function for amplification of motion due to the cantilevered QD0 magnet. Three representative ground motion models were investigated. For the worst-case ground motion model, the Push-Pull detector platform with the simplified rigid-support structure model complies with the vibration tolerance to keep luminosity loss below 1% and can be scaled by 120% while still preserving this constraint.

SUMMARY AND CONCLUSIONS

A thick reinforced concrete platform as envisioned for the ILC or CLIC detectors is expected to have comparable stiffness to the ground on which it rests. It will couple to the ground, hence its eigenfrequencies and eigenmodes are expected to differ somewhat from free-space modes.

The cone model provides an accurate way to incorporate soil-structure interaction into a FEA model. It matched experiment quite well on the SLAC EX-6 block, where coupling effects were particularly egregious due to the small size of the support pads. Effects on ILC and CLIC Push-Pull platforms are expected to be less; these platform simulation efforts are ongoing.

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