4.4 Vibration

Regulatory Setting

Unlike noise, construction-related vibration is not addressed within 23 CFR 772 FHWA Procedures for Abatement of Highway Traffic Noise and Construction Noise, amended, effective July 13, 2011. Similarly, there are no state regulations in New Jersey or local laws within Hudson County which address construction-induced vibration.

On a federal level, the best available guidance on evaluating the effects of construction-related vibration is provided within the Federal Transit Administration's (FTA) Transit Noise and Vibration Impact Assessment guidance manual (FTA-VA-90-1003-06, May 2006). While the Project is not subject to FTA review and approval, this guidance provides vibration source data; vibration propagation equations; and thresholds for identifying the potential for the surrounding community to be annoyed by construction activity, as well as the potential for structural damage to occur. As such, the FTA's guidance manual was utilized to evaluate construction-related vibration impacts.

4.4.1 Construction-Related Vibration Assessment Methodology

Construction for Resist structures will require impact and vibratory hammers to drive piles and sheeting between the piles. The impact and vibratory hammers will be required along the entire length of the Resist feature, as well as at discharge locations in Weehawken Cove. These types of non-typical construction activities would result in the highest construction-related vibration impacts associated with the Project. As such, construction-related vibration levels for these heavy construction activities were calculated for each Build Alternative. The construction duration for this heavy equipment is projected to last 3.5 years (44 months).

Ground-borne vibration effects caused by heavy construction activities are commonly defined in peak particle velocity (PPV). PPV, the maximum instantaneous positive or negative peak of the vibration signal, is measured in inches per second (in/sec). However, human response to vibration is typically referred to in VdB values. VdB is used to describe absolute values of vibration velocity relative to a chosen reference level. The vibration velocity level is reported in decibels relative to a level of 1x10-6 in/sec.

Based on the FTA guidance manual, construction-induced vibration should be quantitatively assessed for activities such as blasting, pile driving, vibratory compaction, demolition, drilling, and excavation in close proximity to sensitive structures because these activities have the greatest potential to generate vibration impacts. Potential structural damage effects are the primary concern with regard to construction-induced vibration. While DSD elements will be constructed utilizing standard construction equipment in locations throughout the Study Area, a construction-related vibration assessment was performed for Resist structures because the construction activities associated with Resist infrastructure pose the greatest risk for structural damage.

Vibratory sheet pile driving was assumed to be performed utilizing a vibratory hammer, while impact pile driving was assumed to be performed through use of an impact pile driving rig. Therefore, the construction vibration assessment was performed for vibratory sheet pile driving and impact pile driving operations. The analysis was performed assuming vibratory sheet pile driving and impact pile driving activities would be necessary along the entire Resist alignment for each of the Build Alternatives. In addition, it was assumed that vibratory sheet pile driving would be necessary for the high-level sewer outfall adjacent to 14th Street for Alternatives 2 and 3 and for the force main outfalls to support DSD at Weehawken Cove for all three Build Alternatives.

Impacts related to construction-generated vibration are typically assessed based on structural damage and annoyance thresholds. Structural damage is based on the PPV of the vibrations (in/sec) and the criteria for assessing damage is based on building material, as presented in **Table 4.24**. Damage criteria and building category definitions listed in the FTA guidance manual are based on the Swiss Standard SN 640 312a. Vibration assessments were conducted for both Building Category II, which represents "typical" buildings in the Study Area, and Building Category IV, which represents poorly-constructed buildings or those that have pre-existing structural damage and are thereby extremely susceptible to vibration-induced damage. While Category IV may

Table 4.24 FTA and Swiss Standard SN 640 312a Construction Vibration Damage Criteria

BUILDING CATEGORY	PPV (IN/SEC)	APPROXIMATE Lv[1]
Category I: Buildings of steel or reinforced concrete, such as factories, retaining walls, bridges, steel towers, open channels, underground chambers and tunnels with and without concrete alignment	0.5	102
Category II: Buildings with foundation walls and floors in concrete, walls in concrete or masonry, stone masonry retaining walls, underground chambers and tunnels with masonry alignments, conduits in loose material	0.3	98
Category III: Buildings as mentioned above in Category II but with wooden ceilings and walls in masonry	0.2	94
Category IV: Construction very sensitive to vibration; objects of historic interest	0.12	90

Note: 1 – [1] RMS VdB re 1 micro-inch/second.

Source: FTA Transit Noise and Vibration Impact Assessment, May 2006. Report No. FTA-VA-90-1003-06 and Swiss Standard SN 640 312a.

Table 4.25 FTA Construction Vibration Annoyance Criteria

LAND USE CATEGORY	GBV IMPACT LEVELS (VDB RE 1 MICRO-INCH/SEC)		
	FREQUENT EVENTS[1]	OCCASIONAL EVENTS[2]	INFREQUENT EVENTS[3]
Category 1: Buildings where vibration would interfere with interior operations	65 VdB[4]	65 VdB[4]	65 VdB[4]
Category 2: Residences and buildings where people normally sleep	72 VdB	75 VdB	80 VdB
Category 3: Institutional land use with primarily daytime use	75 VdB	78 VdB	83 VdB

Notes: 1 –[1] “Frequent Events” is defined as more than 70 vibration events of the same source per day.
2 –[2] “Occasional Events” is defined as between 30 and 70 vibration events of the same source per day.
3 –[3] “Infrequent Events” is defined as fewer than 30 vibration events of the same kind per day.
4 –[4] This criterion limit is based on levels that are acceptable for most moderately sensitive equipment such as optical microscopes. Vibration-sensitive manufacturing or research would require detailed evaluation to define the acceptable vibration levels.

Source: FTA Transit Noise and Vibration Impact Assessment, May 2006. Report No. FTA-VA-90-1003-06.

Table 4.26 FTA Construction Vibration Annoyance Criteria for Special Buildings

LAND USE CATEGORY	GBV IMPACT LEVELS (VDB RE 1 MICRO-INCH/SEC)	
	FREQUENT EVENTS[1]	OCCASIONAL EVENTS[2]
Concert Halls	65 VdB	65 VdB
TV Studios	65 VdB	65 VdB
Recording Studios	65 VdB	65 VdB
Auditoriums	72 VdB	80 VdB
Theaters	72 VdB	80 VdB

Notes: 1 –[1] “Frequent Events” is defined as more than 70 vibration events of the same source per day.
2 –[2] “Occasional or Infrequent Events” is defined as fewer than 70 vibration events of the same source per day.

Source: FTA Transit Noise and Vibration Impact Assessment, May 2006. Report No. FTA-VA-90-1003-06.

include historic buildings, a pre-construction survey will be needed in order to accurately classify the Study Area buildings into appropriate categories. Therefore, the goal of this structural damage assessment is to identify the distances from construction activities and approximate the number of buildings where structural damage could occur if those building categories are present within those distances. The lowest damage threshold and a threshold representative of the “average” building was considered in order to be conservative. The PPV of the vibrations above which there is a potential for damage to a structure in Category II buildings is 0.3 in/sec and 0.12 in/sec for Category IV buildings.

Vibration annoyance is evaluated based on vibration velocity levels (Lv) measured in units of VdB. The human perceptibility threshold is approximately 65 VdB, though response to vibration is not usually significant unless the vibration exceeds 70 VdB. Human response to vibration is a complex topic with limited research. The FTA criteria for assessing annoyance due to construction-related vibrations is general and based on land use categories that are presented in **Table 4.25**.

In accordance with FTA manual guidelines, vibration land use Category 1 is intended to represent other non-residential buildings with high sensitivity such as buildings where vibration-sensitive research and manufacturing is performed, hospitals with vibration-sensitive equipment, and university research operations. Vibration land use Category 2 is intended to represent residences, as well as hotels and hospitals where people sleep. Vibration land use Category 3 is intended to include schools and churches, as well as quiet office buildings where vibration may interfere with activities; however, this category is not intended to include all buildings with office space (e.g., industrial buildings which have office space).

The FTA’s guidance manual also establishes ground-borne vibration limits for a set of land use types, which are extremely sensitive to vibrations and do not fit into the three land use categories described in **Table 4.25**. These land use types are referred to as ‘special buildings’ and include concert halls, television studios, recording studios, auditoriums, and theaters. **Table 4.26** presents vibration annoyance criteria for these ‘special’ building types.

For the construction vibration annoyance assessment, a variety of land uses were identified within the Study Area proximate to the construction operations. Frequent vibration events (i.e., more than 70 events per eight-hour day, per the FTA criterion definition) were assumed; therefore, for Category 3 land use (i.e., institutional land use with primarily daytime use), vibration velocity levels above 75 VdB would be considered annoying. Category 3 land use within the Study Area were identified as primary and secondary schools, churches, Stevens Institute of Technology, and office buildings.

Category 1 (high sensitivity) land use, associated with Stevens Institute of Technology university research operations, were identified within the Study Area. Upon review of the university’s website, Stevens maintains several research laboratories within the Engineering, Sciences, Computer Sciences, and Arts and Humanities departments, which host potentially vibration-sensitive operations and include potentially vibration-sensitive equipment. Based on field reconnaissance, in addition to the research labs, classroom laboratories with potentially vibration-sensitive equipment were identified. Vibration velocity levels above 65 VdB would be considered annoying to this land use category.

A vibration annoyance assessment was not performed for residential land use Category 2. As outlined in the FTA's guidance manual, Category 2 is intended to cover locations where people sleep (e.g., residences, hotels, hospitals, etc.). Therefore, the FTA Category 2 annoyance criterion is intended to represent nighttime sensitivity. As previously stated, the NOHRHC prohibits nighttime work, so the potential for annoyance was not evaluated for FTA Category 2 land use.

In addition to Category 1 and 3 land use identified, the music and technology department at Stevens Institute of Technology has a recording studio, located in the Morton-Peirce-Kidde complex. The University also has several auditoriums (e.g. Edwin A Stevens building and Babbio Center). These facilities would be classified as 'special buildings' under FTA. Vibration velocity levels above 65 VdB would be considered annoying to people utilizing the recording studio, while levels above 72 VdB would be considered annoying in the campus auditoriums. Table 12-2 of FTA's May 2006 guidance manual includes a list of construction equipment with reference vibration source levels in PPV and VdB at a distance of 25 feet. The reference source levels are representative of a variety of measured data. Although soil conditions can affect actual vibrations, FTA guidance states that these reference source levels provide a reasonable estimate for a wide range of soil conditions. For each sheet pile operation, the upper range value of a sonic (vibratory) pile driver was utilized to perform a conservative worst-case analysis. Similarly, the upper range value of a pile driver (impact) was utilized to perform a conservative worst-case analysis.

Reference source levels are propagated to sensitive receivers based on Equations 1 and 2, which are provided in the FTA's guidance manual. Equation 1 was utilized to perform the construction vibration damage assessment and includes a factor "n" to account for the attenuation rate of vibrations through the ground in accordance with FTA procedures. The value of "n" may be varied if detailed soil information is known. An "n" value of 1.5 is representative of "competent soils" (including sand, sandy clays, silty clays, silts, gravel, and weathered rock). Equation 2 was utilized to predict vibration velocity levels for the annoyance assessment.

$$(1)\ PPVequip = PPVref * \left(\frac{25}{D}\right)^{n}; \text{ and}$$

$$(2)\ Lv(D) = Lv(25ft) - 30\log\left(\frac{D}{25}\right)$$

Where:

PPVref = reference vibration level in in/sec at 25 feet.

D = distance between source and receptor (feet).

n = attenuation rate of vibrations through the ground.

Equations 1 and 2 were manipulated to determine the distances from the impact and vibratory pile driving operations within which structural damage and annoyance is anticipated for each building type and land use type assessed, respectively. Results of the construction-generated vibration damage assessment for the sheet driving and impact pile driving operations were compared to structural damage and annoyance criteria to assess vibration-related impact.

4.4.2 Environmental Consequences

Construction-related vibration damage assessments for vibratory sheet pile driving and impact pile driving operations were performed for each alternative. As previously detailed, damage analyses were performed for two different building categories: Category II, which is intended to represent the "average" building construction in the Study Area and Category IV, which represents buildings extremely susceptible to vibration damage. A pre-construction survey is needed to classify Study Area buildings into the appropriate category. Modeling procedures are conservative and assume a homogeneous ground type between construction activities and buildings.

Resist structure alignments have been conceptually designed so actual locations of vibratory pile driving versus impact pile driving is unknown at this time. Assuming one sheet or pile is driven at any given time, there is a potential for structural damage as a result of construction of each alternative.

The distances in which there is a potential for structural damage to occur to Building Category II and IV buildings in the Study Area were predicted based on individual vibratory sheet pile and impact pile driving activities along the entire alignment. In addition, the analysis assumed that operations would be separated by enough distance that vibrations from multiple operations would not cumulatively affect buildings within the Study Area. Source levels for vibratory sheet pile driving and impact pile driving assumed conservative source levels provided within guidelines. Examples of structural damage include loosening of paint and small plaster cracks, loosening and falling of plaster, cracks in masonry, structural weakening, affected ability for load support, etc.

Vibration analyses indicate that potential structural damage for Building Category II ("average" building construction) may occur for all such buildings within 45 and 74 feet of vibratory sheet pile and impact pile driving activities, respectively. In addition, potential structural damage for Building Category IV (buildings extremely susceptible to vibration damage) may occur for buildings within 84 and 136 feet of vibratory sheet pile driving and impact pile driving operations, respectively. Minimum distances to potential structural

Table 4.27 Potential Structural Damage Assessment Results - Minimum Distance to Potential Structural Damage

BUILDING CATEGORY[1]	MINIMUM DISTANCE TO STRUCTURAL DAMAGE (FEET)	
	VIBRATORY SHEET DRIVING OPERATIONS	IMPACT PILE DRIVING
Category II	45	74
Category IV	84	136

Notes: 1 - Building Category II - Buildings with foundation walls and floors in concrete, walls in concrete or masonry, stone masonry retaining walls, underground chambers and tunnels with masonry alignments, conduits in loose material; Damage Threshold 0.30 in/sec.
2 - Building Category IV - Construction very sensitive to vibration; objects of historic interest; Damage Threshold 0.12 in/sec.

Source: Paul Carpenter Associates, Inc., 2016.

damage for both building categories is detailed within **Table 4.27**.

Of the two operations, impact pile driving is predicted to result in potential structural damage to 'typical' and poorly constructed buildings at a greater distance than vibratory sheet pile driving. The extent of potential structural damage is greater for impact pile driving operations than for vibratory pile driving due to higher source vibration levels associated with impact pile driving. Therefore, contours depicting distances to potential structural damage from the locations of impact pile driving activities for each alternative have been developed. The number of structures with the potential to sustain damage during vibratory or impact pile driving activities is dependent on the alignment of each Resist structure alternative.

Construction-related vibration annoyance assessments for vibratory sheet pile driving and impact pile driving operations were performed for each alternative. As previously detailed, analyses were performed for Category 1 land use, which represents buildings where vibration would interfere with interior operations and Category 3 land use, which represents institutional land use with primarily daytime use. Category 3 land use also includes "special buildings," as a result of a recording studio and auditoriums located within Stevens Institute of Technology. Examples of annoyance associated with ground-borne vibration may include perceived movement within buildings, rattling of items such as windows or household objects located on shelving or in cabinets, disruption of vibration-sensitive equipment or activities, etc.

Based on equation 2, described above, potential vibration annoyance distances for each category were developed. Category 1 building occupants within 539 feet of vibratory pile driving and 922 feet of impact pile driving activities have the potential to be annoyed. Category 3 building occupants within 250 feet from vibratory pile driving and 428 feet from impact pile driving activities have the potential to be annoyed. Concert halls, TV studios, and recording studio occupants ("special buildings") within 539 feet of vibratory pile driving and 922 feet of impact pile driving activities have the potential to be annoyed. Auditoriums and theater occupants ("special buildings") within 315 feet of vibratory pile driving and 539 feet of impact pile driving activities have the potential to be annoyed.

Based on vibration source levels provided within the FTA guidance manual, DSD construction-related equipment produce much lower vibration levels than impact and vibratory pile driving activity, which are necessary to install Resist features.

Alternative 1

Figure 4.49 depicts the boundaries of the areas where Category II and Category IV buildings could be potentially impacted by pile driving activities under Alternative 1. Based on a review of aerial mapping, the total number of structures within 74 feet of impact pile driving is 56 and the total number of buildings within 136 feet of impact pile driving is 94. It is important to note that the confirmation of the number of structures identified within the impact driving distances that meet the criteria for either Category II or Category IV buildings would be based on pre-construction surveys.

There are many research and classroom laboratories located at Stevens Institute of Technology. Therefore, it is difficult to identify all vibration-sensitive equipment located within these labs. Further, given changes in coursework and research operations, the degree of vibration-sensitivity may change over time. Laboratories at Stevens are within distances to potential annoyance for impact and vibratory pile driving associated with Alternative 1 Resist features. Similarly, the recording studio in the Morton-Peirce-Kidde complex is within the distance to annoyance for impact pile driving associated with Alternative 1. Auditoriums located in the Edwin A. Stevens building and Babbio Center are within distances to annoyance for both impact and vibratory pile driving associated only with Alternative 1. In the event Alternative 1 is pursued, further investigation and coordination with the University would need to be performed under final design to identify all vibration-sensitive equipment that would be utilized in research and classroom labs, as well as any vibration-sensitive activities that would occur during construction. Coordination with the University will also be performed related to use of the recording studios and auditoriums during construction.

Under Alternative 1, there is a potential for minor to severe structural impacts to 56 to 94 buildings.

Alternative 2

Figure 4.50 depicts the boundaries of the areas where Category II and Category IV buildings could be potentially impacted by pile driving activities under Alternative 2. Based on a review of aerial mapping, the total number of structures within 74 feet of impact pile driving is 61 and the total number of buildings within 136 feet of impact pile driving is 104. It is important to note that the confirmation of the number of structures identified within the impact driving distances that meet the criteria for either Category II or Category IV buildings will be based on pre-construction surveys. Under Alternative 2, there is a potential for minor to

Figure 4.49 Structural Damage - Impact Pile Driving- Alternative 1

Figure 4.50 Structural Damage - Impact Pile Driving- Alternative 2

severe structural impacts to 61 to 104 buildings.

Alternative 3

Figure 4.51 depicts the boundaries of the areas where Category II and Category IV buildings could be potentially impacted by pile driving activities under Alternative 3. Based on a review of aerial mapping, the total number of structures within 74 feet of impact pile driving is 65 and the total number of buildings within 136 feet of impact pile driving is 103. It is important to note that the confirmation of the number of structures identified within the impact driving distances that meet the criteria for either Category II or Category IV buildings will be based on pre-construction surveys. Under Alternative 3, there is a potential for minor to severe structural impacts to 65 to 103 buildings.

No Action Alternative

There would be no vibration impacts on any buildings under the No Action Alternative, nor any vibration-related annoyance.

4.4.3 Mitigation Measures and BMPs in Alternatives 1, 2, and 3

Based on the results of the vibration assessments, construction has the potential to cause structural damage to Category II buildings (buildings with foundation walls and floors in concrete, walls in concrete or masonry, stone masonry retaining walls, underground chambers, and tunnels with masonry alignments) within 45 feet of vibratory pile driving and 74 feet of impact pile driving. Therefore, in order to mitigate the potential extent of structural damage from impact pile driving, a vibratory hammer may be utilized. Alternatively, piles can be cast-in-place utilizing an auger drill, which reduces potential structural damage to Category II buildings within 11 feet of drilling.

In addition, construction has the potential to cause structural damage to Category IV buildings (construction very sensitive to vibration; objects of historic interest) within 84 feet of vibratory pile driving and 136 feet of impact pile driving. Therefore, in order to mitigate the potential extent of structural damage from impact pile driving, utilizing a vibratory hammer for both sheet and pile driving is suggested. Alternatively, piles can be cast-in-place utilizing an auger drill, which reduces the potential to cause structural damage to Category IV buildings to within 20 feet of drilling.

As described earlier, vibration annoyance can be anticipated for Category 1 (buildings where vibration would interfere with interior operations) land use, as well as certain 'special buildings' (concert halls, TV studios, and recording studios). In addition, vibration annoyance can be anticipated for Category 3 (institutional land use with primarily daytime use) land use. For auditoriums within the Edwin A. Stevens building and Babbio Center, vibration annoyance can be anticipated.

Therefore, in order to mitigate vibration annoyance, a vibratory hammer may be utilized for both sheet and pile driving. Alternatively, piles can be cast-in-place utilizing an auger drill. This method reduces the potential to cause vibration annoyance to Category 1 buildings to within 63 feet and Category 3 buildings to within 135 feet of drilling. If Alternative 1 is selected, university research and classroom labs would not experience vibration-induced annoyance if drilled piles are utilized. Further, the recording studio in the Morton-Peirce-Kidde building and auditoriums in the Edwin A. Stevens building and Babbio Center would also not experience annoyance if an auger drill is utilized.

While FTA lists use of vibratory hammers and drilled piles as alternative construction methods for reducing impact, these methods may not be feasible everywhere due to schedule delay and cost constraints. Critical locations where alternative construction methods, specifically drilled piles, would be utilized would be identified during final design and specified within contract documents.

In addition to alternative construction methods associated with the Resist elements, for both DSD and Resist, establishing construction vibration structural damage response action and stop-work levels are recommended for inclusion within contract documents. Such levels will be established during final design and after pre-construction surveys have been performed to identify the structural integrity of Study Area buildings and other existing pre-construction issues.

Strong community outreach will be conducted throughout the design and construction process to explain what people should expect to feel during heavy construction and ensure public safety. In-person communications and digital communication through the project website and email updates would provide routine updates to affected residents. Further, in the event that Alternative 1 is selected, detailed coordination with Stevens Institute of Technology must be performed to identify specific vibration-sensitive equipment and research operations that would be on-going during construction, as well as use of the recording studio and auditoriums in the Edwin A. Stevens building and Babbio Center. At that time, specific minimization and avoidance measures will be identified, as needed.

Recommended vibration control measures and standard specifications that should be implemented into contract documents include:

- establish construction vibration structural damage response action and stop-work levels;
- conduct a pre-construction survey of all buildings within 136 feet of the Resist structure, appropriately classify as Category II or Category IV, and identify existing cracks and building conditions;
- require use of drilled piles and specify locations along Resist alignment where this requirement is applicable;
- require the development and implementation of a Vibration Control and Monitoring Plan, which documents expected vibration levels during driving

Figure 4.51 Structural Damage - Impact Pile Driving- Alternative 3

activities and methods to control vibration;

- require third-party compliance construction vibration monitoring; and
- contractor will be responsible for damage to structures resulting from noncompliance with the vibration control and monitoring plan or determined to be related to the contractors work during the construction of this project.

Once final design and construction staging plans have been completed, the findings of this vibration analysis can be revisited, if required, to determine whether there are any significant changes to the findings and recommendations.