Technical Memorandum

To: James Clift (EGLE) and Ryan Mitchell (MDOT)	Project: Enbridge Line 5 Tunnel Project
From: Sam Swartz	cc: Dan Adams, David Crouthamel, Marco Moccichino
Date: January 12, 2021	Job No.: 6191.0
Subject: Vibration Impacts of the Enbridge Line 5 Tunnel Project	

1.0 Introduction and Question

The Enbridge Line 5 Tunnel Project is anticipated to utilize a slurry tunnel boring machine (TBM) to excavate an approximately 4 mile tunnel below the Straits of Mackinac that will house the new section of the Line 5 pipeline as replacement of the two existing pipelines on the lakebed of the Straits. The TBM is anticipated to excavate through bedrock with high hydrostatic pressure (up to 17 bars from available information) and with the potential for highly fractured and poor rock conditions. Depth to the tunnel, measured from the mudline, ranges from 60 feet near the south shoreline, to over 350 feet near the middle of the tunnel.

This document discusses the potential impacts due to vibrations caused by the tunnel boring machine (TBM) during the excavation of the Line 5 Tunnel Project. It addresses the following questions raised by the EGLE Representative on October 20, 2020 (received via email) as part of the permit review process:

"Discuss impacts of vibrations, including the expected range of impacts considering the geology, from TBM excavation on existing pipeline, lakebed, whitefish spawning area, and potential for liquefaction, amongst others."

2.0 Answer to Question

As a TBM excavates through the ground, vibrations are primarily given off by the rotation of the cutterhead and excavation of the ground. These vibrations tend to be higher for larger TBMs, and for TBMs in rock. These vibrations tend to be continuous steady state vibrations compared to shorter duration vibrations. Vibrations are also given off by equipment within the tunnel, as well as transport systems within the tunnel, but these vibrations tend to be lower than the TBM itself. Vibrations generally dissipate with distance away from the TBM. Vibrations are often given in "particle velocity" or "peak particle velocity" (PPV), in inches per second.

Vibrations from TBM excavations have been measured for multiple projects in the past, and correlations have been developed for dissipation of vibrations away from the vibration source, at the TBM heading.

The majority of the tunnel alignment, except right near the shorelines, is in excess of 75 feet in depth. In general, for depths greater than 75 feet, PPV vibrations from TBMs are on the order of 0.1 inches per second or less from available data on dissipation of vibrations. Vibrations would dissipate quickly with further distance (depth) from the TBM. More specific analysis can be performed for certain situations where more sensitive structures occur, as discussed below.

For impacts to the existing pipelines resting on the bottom of the Straits, a typical conservative PPV vibration to cause impacts is at least 0.5 inches per second, and could be higher if pipeline encasement or embedment is considered. This value is at least five times higher than anticipated vibrations, and thus impacts are very unlikely.

For impacts to whitefish spawning areas, vibrations of the magnitude expected are very unlikely to cause significant disruptions. These areas tend to be primarily coarser-grained deposits, mostly gravel and rock, and thus are not as susceptible to being stirred up or displaced by vibrations. However, it may be advisable if spawning areas occur in closer proximity to the tunnel to excavate the tunnel outside of the spawning windows, which typically takes place in the later fall at night.

For potential for liquefaction, while soils within the Straits may be susceptible to liquefaction if subjected to high enough cyclical deformations from large vibrations, typical PPV vibrations to instigate liquefaction or consolidation are on the order of at least 0.5 inches per second for soils of similar depositional environments, if not significantly higher. This limit is similar for vibration induced settlement or compaction in coarser-grained soils. This value is at least five times higher than anticipated vibrations, and thus liquefaction or consolidation induced by these vibrations is also very unlikely.

For concerns for the lakebed, archeological significant sites were identified as a specific concern. Other concerns would likely have similar or less conservative overall behavior. For more sensitive structures, a typical conservative PPV vibration to cause impacts can be as low as 0.1 inches per second, often used for very sensitive structures. Anticipated vibrations could be around this level for shallower portions of the tunnel. Deeper portions are likely to experience lower vibrations. While impacts are not anticipated, if there are specific known locations of these archeological sites, it is recommended to do location-specific analyses. These analyses would account for actual offsets from the tunnel and attempt to make a better estimate of vibrations that may impact the sites.

In conclusion, vibrations from TBM excavation are very unlikely to cause impacts to the existing pipeline, whitefish spawning areas, nor liquefaction. For more sensitive sites on the lakebed especially closer to the current shorelines, while impacts are not likely to occur, it is recommended to do location-specific analyses to verify potential impacts.

3.0 Discussion

3.1 TBM Vibrations

For further discussion on TBM vibrations, information has been gathered from multiple sources from past projects. Vibrations are often quantified as “particle velocity” or “peak particle velocity” (PPV), in inches per second. Vibrations are often measured with seismographs, recording vibrations in three orthogonal directions. PPV takes the maximum, or a combination of the maximum values. Vibrations generally dissipate with distance away from a point source. This dissipation is often logarithmic and is dependent on the type of ground. In this section both analytical approaches and case histories of similar diameter TBM tunnels are presented, as a means of estimating the rate of dissipation of vibrations with distance.

While conditions identical to this project are not available, a general understanding of the magnitude of vibrations can be estimated from TBM excavation. Data from past projects indicate that TBM vibrations are low, especially compared to other types of construction such as drill and blast rock excavation. The vibrations tend to be higher for larger TBMs, and for TBMs in rock, as more energy is applied to the ground to excavate the tunnel. These vibrations tend to be continuous steady state vibrations over a short period of time (typically 30 minutes to an hour), as the TBM is advancing. Frequencies at which TBM vibrations occur are typically in the range of 10 to 100 Hz, more often in the 10 to 30 Hz or 10 to 40 Hz range. Vibrations are also given off by equipment within the tunnel, as well as transport systems within the tunnel, but these vibrations tend to be similar or lower than the TBM itself. Table 1 and Figures 1 and 2 that show vibration versus distance are shown below, from Flanagan (1993). Data indicates that at a distance of approximately 75 feet (25-m), vibrations are likely less than or well less than 0.1 inch per second (2 to 3-mm per second). 75 feet has been selected as a typical lower cover, although slightly shallower portions of the tunnel may occur within 500 to 1000 feet of the shorelines. A project specific vertical alignment has been reviewed to confirm these assumptions.

Table 1 - Typical peak particle velocity intensities at varying distances from construction equipment.

Equipment	Distance		
	5m	10m	25m
Jack hammer	1.7	0.6	0.1
Trucks	3.0	1.1	0.3
Large bulldozer	3.9	1.4	0.3
TBM (hard rock)	5.5	2.2	0.6
Pavement breaker with 1.8m drop	18	6.0	1.8
Vibratory pile driver	30	12	2.8

Note: peak particle velocity units are mm/s

Table 1: Typical Peak Particle Velocity Intensities at Varying Distances from Construction Equipment (Flannagan 1993)

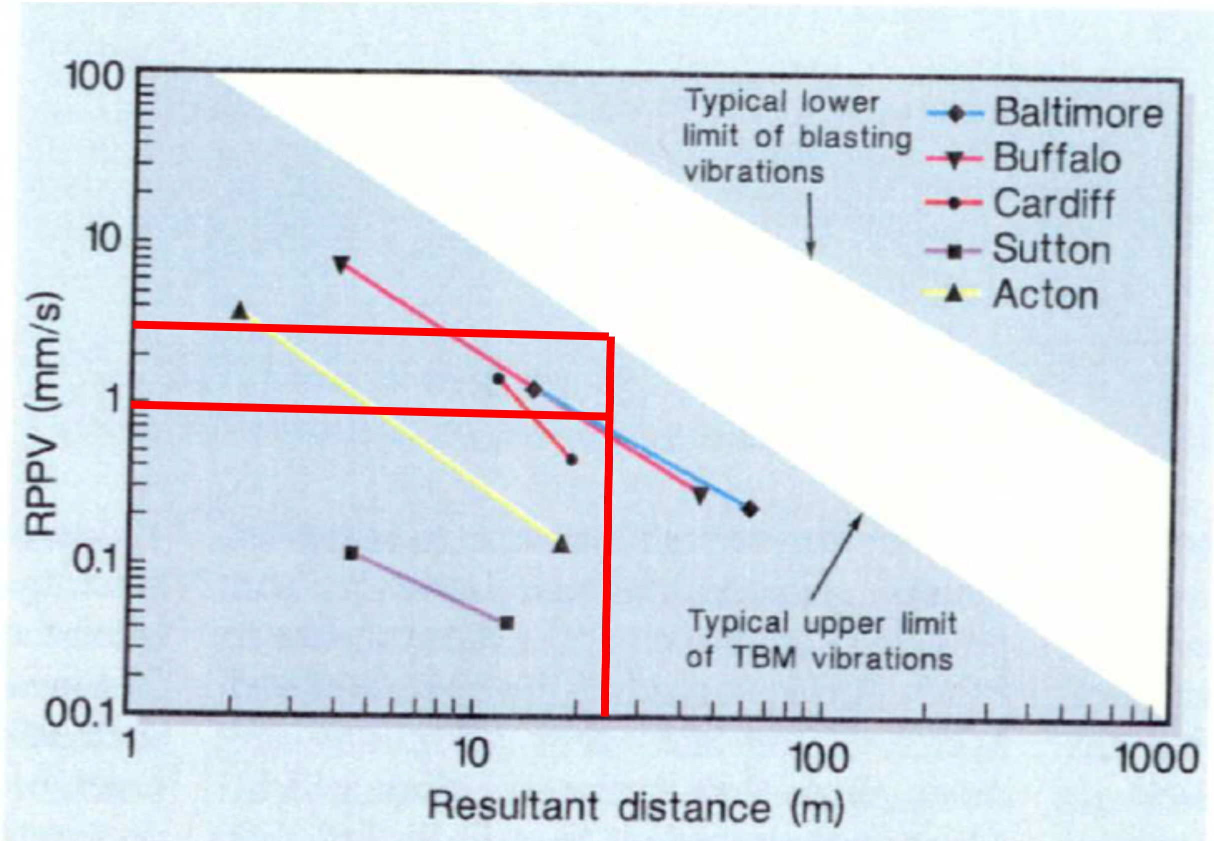

Figure 1: TBM Vibration Attenuation Data from Prior Projects (Flannagan 1993)

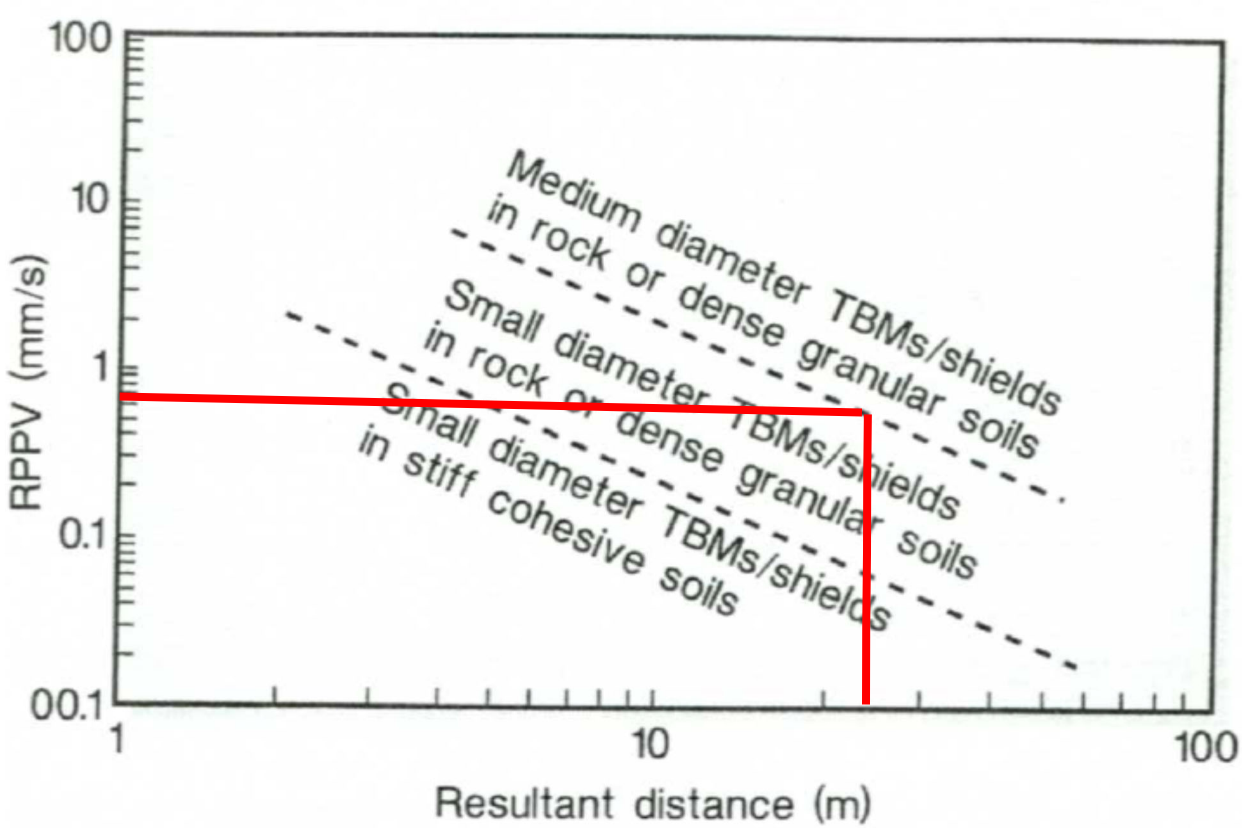

Figure 2: Vibrations from Small to Medium sized TBMs (Flannagan 1993)

Other data sources provide very similar results. Data from Carnevale et al (2000) for monitoring vibrations above the MetroWest Water Supply Tunnel near Boston indicated vibrations up to approximately 0.005 to 0.01 inches per second at depths in excess of 200 feet, mostly in hard rock. From Figures 1 and 2, at about a distance of 60 m (roughly 200 feet), upper bound vibrations are approximately 0.3 to 0.7 mm per second, or 0.01 to 0.03 inches per second.

One common equation for vibration dissipation is shown below, from the Transportation and Construction-Induced Vibration Guidance Manual (Caltrans, 2004). In this equation, v_a is the vibration amplitude at a distance from the source of r_a, v_b is the vibration amplitude at a distance r_b, and a is a material dampening coefficient, dependent on the ground. The dampening coefficient is typically assumed to be 0.03 per foot in softer rock, or closer to 0.1 per foot in softer soils.

$$v_b = v_a \left(\frac{r_a}{r_b}\right)^{0.5} e^{a(r_a - r_b)}$$

Using this equation, and setting a near-source vibration at approximately 15 feet (5 m) from the source equal to between 0.2 and 0.3 inches per second (5 to 8 mm per second), which is generally consistent with Table 1 and Figures 2 and 3, vibrations at approximately 75 feet (25 m) would be approximately 0.015 to 0.025 inches per second for soft rock (and quite a bit lower for soil).

In conclusion, while perceptible at shallower depths for certain situations, in general TBM vibrations are often hard to detect. From all the information above, an upper bound vibration of approximately 0.1 inches per second is anticipated for a depth of approximately 75 feet. As the depth of the tunnel is typically greater than 75 feet, this level of vibration can be considered as an upper bound on potential vibrations. If needed, more detailed assessments of vibrations versus depths or offsets can be performed, including for near-shore locations where depths may be slightly less than 75 feet. See Section 3.4 below for locations where further analysis may be warranted.

3.2 Vibrations to Cause Pipeline Impacts

While not numerous, some studies have been published on vibrations required to impact structures, such as pipelines. The majority of the studies have considered impacts from drill and blast operations, not from TBMs. Tables from the Transportation and Construction-Induced Vibration Guidance Manual (Caltrans, 2004), detail limits defined by various researchers. Table 10 summarizes the Swiss Association for Standardization for impacts to structures. In general, the pipelines should fall into the range of Class I Structures, but Class II would be a conservative assumption. For frequencies caused by TBMs, data indicates a range of values, but often in the 10 to 100 Hz range. Per Table 10, Class II limits on PPV are approximately 0.3 inches per second for a Continuous Source. Class I limits are approximately 0.5 inches per second for a Continuous Source.

Table 10. Swiss Association of Standardization Vibration Damage Criteria

Building Class	Continuous Source PPV (in/sec)	Single-Event Source PPV (in/sec)
Class I: buildings in 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	1.2
Class 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	0.7
Class III: buildings as mentioned above but with wooden ceilings and walls in masonry	0.2	0.5
Class IV: construction very sensitive to vibration; objects of historic interest	0.12	0.3

As another table from the Transportation and Construction-Induced Vibration Guidance Manual (Caltrans, 2004), the American Association of State Highway and Transportation Officials (AASHTO, 1990) also identifies maximum vibration limits. For Engineering structures, which would include the pipelines, limiting velocity is 1 to 1.5 inches per second.

Table 15. AASHTO Maximum Vibration Levels for Preventing Damage

Type of Situation	Limiting Velocity (in/sec)
Historic sites or other critical locations	0.1
Residential buildings, plastered walls	0.2–0.3
Residential buildings in good repair with gypsum board walls	0.4–0.5
Engineered structures, without plaster	1.0–1.5

Limits on vibrations are typically specified for projects with larger anticipated vibrations, primarily from drill and blast operations. These specified limits are often set as a function of frequency, but range from approximately 0.75 inches per second up to 2 inches per second.

Based upon all information above, criteria for pipelines of between 0.3 inches per second to over an inch per second are consistently provided. As a generally conservative criterion for engineering steel structures, it is recommended to use 0.5 inches per second for the existing pipelines.

3.3 Vibrations to Cause Impacts to Fish Habitats

Information for fish habitats was gathered from in-house experts on fish biology. While the specific issue for TBM vibrations has not commonly been encountered, vibrations from pile driving for bridges and other structures in proximity to fish spawning habitats is more common. For most fish spawning habitats, which includes whitefish spawning areas, bedding material is primarily coarser-grained, ranging from ¼” to 5” gravel or rubble, with a general lack of fine material (less than 10%). Typical gravel used to create these habitats is shown in Figure 3 below. If vibrations were to occur, it is anticipated that slight consolidation and migration of fines downward would occur. This behavior could actually slightly improve the habitat. However, it might be advisable that if spawning areas are known to be in close proximity to the horizontal tunnel alignment, to attempt to limit TBM excavation to times outside of the spawning window. The spawning window for whitefish is in the late fall, from mid-October to early December, usually taking place at night. Section 4 provides a website with further information on whitefish spawning habitat and overall timing.

Figure 3. Typical Gravel for Spawning Beds

3.4 Vibrations to Cause Liquefaction

Deformation and settlement of coarse-grained soils during vibrations and cyclic loading have been studied for both pile-driving induced settlements, and liquefaction potential for seismic events. Determining site-specific recommendations requires extensive geotechnical information and a thorough understanding of the vibration sources. While a detailed assessment is challenging for this project due to limited site-specific information, the following discussions provide some background on vibrations that can induce settlement and/or liquefaction.

For settlements due to pile driving, Mohamad and Dobry (1987) provided a method to analyze the threshold or critical surface peak particle velocity that triggers consolidation and settlement of coarser grained soils. The calculation of this velocity can be performed if data is available on soil shear wave velocity, shear degradation behavior of the soil, and depth of consideration. This information is limited without significant additional efforts to compile and analyze data. However, this paper cites a study of a couple of project sites in the Bay Area in California where pile driving was performed in loose fill and sand deposits. These sites were analyzed, and it was found that a critical velocity of at least 16.8 mm/s (0.66 in/s) was needed to cause consolidation. This value can be used as a reasonable conservative estimate for vibration induced consolidation.

For seismic induced liquefaction, a soil cyclic shear strain can be estimated by dividing the soil velocity from vibrations (PPV) by the shear wave velocity of the in-situ soils. This cyclic shear strain can then be used to estimate an excess pore pressure in the soil. If the excess pore pressure gets high enough to overcome the in-situ effective stress, liquefaction can occur. A detailed analysis requires shear wave velocity of the soils, and soil-specific correlations between cyclic shear strain and excess pore pressure. However, a simplified approach can be taken by making conservative assumptions on input to the analysis and determining the velocity (PPV) that would cause liquefaction. Taking this simplified approach and conservative assumptions, an approximate velocity to cause liquefaction is approximately 0.6 inches per second, consistent with roughly 0.01% shear strain, which is an approximate limit where excess pore pressures start to develop.

Based upon potential for both vibration-induced consolidation and liquefaction, past case histories and conservative analyses indicate that vibrations must exceed at least 0.5 inches per second, if not higher, to trigger these behaviors.

3.5 Vibrations to Cause Impacts to Sensitive Structures

Similar to the discussion above in Section 3.2, studies have been conducted to determine impacts from vibrations on more sensitive structures. Using the same Table 10 above, but assuming that any archeological sites would be more sensitive to vibrations, say Class IV Structures, limits on vibrations would be closer to 3 mm/s, or just over 0.1 inches per second.

As another table from the Transportation and Construction-Induced Vibration Guidance Manual (Caltrans, 2004) in Section 3.2 above, the American Association of State Highway and Transportation Officials (AASHTO, 1990) also identifies maximum vibration limits for Historic Sites or other critical locations, limiting velocity to 0.1 inches per second.

Konan (1985) also documented criteria for sensitive buildings. Table 11 below comes from the Transportation and Construction-Induced Vibration Guidance Manual (Caltrans, 2004). For lower frequencies anticipated during tunneling, a limit for steady-state vibration of 0.12 inches per second is recommended.

Table 11. Konan Vibration Criteria for Historic and Sensitive Buildings

Frequency Range (Hz)	Transient Vibration PPV (in/sec)	Steady-State Vibration PPV (in/sec)
1–10	0.25	0.12
10–40	0.25–0.5	0.12–0.25
40–100	0.5	0.25

Dowding (1996) also documented criteria for various buildings. Table 14 below comes from the Transportation and Construction-Induced Vibration Guidance Manual (Caltrans, 2004). A limit for vibration of 0.5 inches per second is recommended.

Table 14. Dowding Building Structure Vibration Criteria

Structure and Condition	Limiting PPV (in/sec)
Historic and some old buildings	0.5
Residential structures	0.5
New residential structures	1.0
Industrial buildings	2.0
Bridges	2.0

Table 19 below is the final recommendations from the Transportation and Construction-Induced Vibration Guidance Manual (Caltrans, 2004). Depending upon the sensitivity of the structures, limits of between 0.08 and 0.25 inches per second are recommended.

Table 19. Guideline Vibration Damage Potential Threshold Criteria

	Maximum PPV (in/sec)	
Structure and Condition	Transient Sources	Continuous/Frequent Intermittent Sources
Extremely fragile historic buildings, ruins, ancient monuments	0.12	0.08
Fragile buildings	0.2	0.1
Historic and some old buildings	0.5	0.25
Older residential structures	0.5	0.3
New residential structures	1.0	0.5
Modern industrial/commercial buildings	2.0	0.5

Note: Transient sources create a single isolated vibration event, such as blasting or drop balls. Continuous/frequent intermittent sources include impact pile drivers, pogo-stick compactors, crack-and-seat equipment, vibratory pile drivers, and vibratory compaction equipment.

Other references indicate that even tighter limits are warranted. Zafiropoulou et al (2018) references limits on vibrations for construction of the Athens Metro in Greece. Very tight criteria were set for "Monuments, archeological findings, and Exhibits in archeological Museums", for example.

From various criteria above, without further information on the sites in question, it is recommended to use 0.1 inches per second as a limiting criteria, consistent with most of the literature. As this limit is similar in magnitude to conservative estimates of vibrations at depths of 75 feet or greater, more site-specific analyses may be warranted for very sensitive structures at shallow depths. To perform these analyses, station and offset of the sites relative to the tunnel to determine a better estimate of offset from the tunnel. Figures and/or equations from Section 3.1 could be used to estimate vibrations at anticipated offsets. Vibrations could then be compared to values above to determine potential risks. Note that because vibrations dissipate by distance per an exponential relationship, sites offset from the tunnel and/or at deeper depths than 75 feet are likely to experience very small vibrations.

4.0 References and Additional Information

A number of publications were used to develop the above response and discussion, as follows:

- California Department of Transportation (Caltrans), Environmental Program, Environmental Engineering, Noise, Vibration and Hazardous Waste Management Office. “Transportation- and Construction-Induced Vibration Guidance Manual”, June 2004.

- Carnevale, M., Young, G., Hager, J., Carnevale, M.C. “Monitoring of TBM-induced ground vibrations”, *North American Tunneling 2000*.

- Flanagan, R. F. “Ground vibration from TBMs and shields”, *Tunnels and Tunnelling*, Oct. 1993 (30-33).

- Mohamad, R., Dobry, R. “Settlement of Cohesionless Soils Due to Piling Vibrations”, *9th Southeast Asian Geotechnical Conference*, Bangkok, Thailand, December 1987 (7-23 to 7-30).

- Zafiropoulou, V.,Vogiatris, K., Mouzakis, H. “A Methodology for Assessing Ground Borne Noise and Vibration Transfer Functions “Tunnel wall-Soil surface” for Metropolitan Rail Networks using the TBM Muck Train as a linear source: Measurements Campaign in the extension of Athens Metro Line 3 towards Piraeus”, *Conf. Proceedings Euronoise 2018* (1321-1328).

In addition, a website with useful information on whitefish spawning is as follows:

- Whitefish Spawning information: https://www.dnr.state.mn.us/minnaqua/speciesprofile/lake_whitefish.html