Newsletter #25

Allowable Peak Particle Velocities for Segmental Pipe through
Limitation of Angular Rotation and Compressive Stresses in Pipe Joints

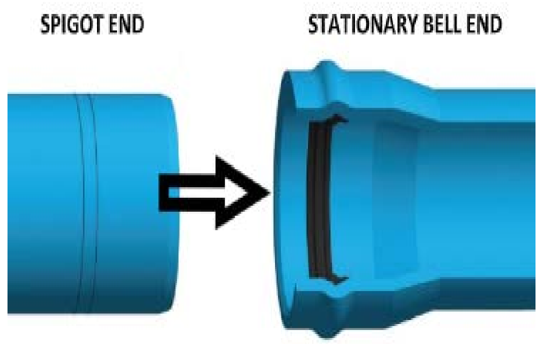

Figure 1 (above), Rotation within a typical bell and spigot joint (ADP,2021); Figure 2 (right), Typical bell and spigot PVC pipe with rubber gasket

This newsletter summarizes several methods to assess the potential of vibrations to damage segmented pipes. A more complete version is available on request. While a good deal is known about the response of continuous pipe to vibratory ground motions, less is known about response of segmented pipe. Described are two methods based upon joint behavior of Ductile Iron Pipe (DIP), PVC plastic pipe and reinforced concrete pipe (RCP) as well as results of the USBM measurements of blast response of jointed PVC plastic pipe.

Joint assessment methods are based upon a) allowable joint rotation and b) axial compressive failure. The allowable joint rotation approach limits peak particle velocity (PPV) of the segmented pipe joint to the statically allowable joint rotation during construction. The compressive failure approach limits vibration (PPV) induced axial compressive stresses to the compressive strength of the pipe material divided by a factor of safety.

Assessment involves both pipe as well as blasting and geological considerations. Three types of pipe joints are considered; concrete, PVC plastic, and DIP iron. Typical segment lengths were assumed to range between 10 and 20 ft (3 and 6 m). Dominant excitation frequency was assumed to range between 25-100 Hz with shear wave propagation velocities, cs, from 1,220 to 2,745 m/sec.

First consider limitation of PPV by limiting joint rotational distortion. For simplicity the calculations assumed the lowest allowable static joint rotation of 0.036 degrees for all pipes no matter their type. Allowable static rotations for PVC and DIP varied from 4 to 0.4 degrees or 0.07 to 0.007 x/SL in Figure 1 (WSSCWater, 2021) where x is the displacement along one segment length, SL. Given the variable allowable rotation for concrete pipe, inspection criterion for RCP from Indiana were employed (Indiana, 2021). They recommend notation of joint openings of 0.1in. or 2.5 mm when checking for piping (intrusion) of silt (through inward water leakage) through the joints. Assuming that ½ of the notation value was tolerable, 0.05 in., the angular distortion of a 2 m (6.5 ft) diameter pipe would be tan-1 (x/SL in Figure 1) or tan1(0.05/(6.5*12)=0.0006) = 0.036 degrees. This allowable rotation is 1/10th that of the most conservative allowable rotation for joints in DIP and PVC pipe, and was used to determine the allowable PPV

Allowable joint rotation can be found by differentiating the ground displacement, u – x relationship for a sinusoidal wave and results in the relationship between allowable slope, du/SL, or rotational angle and allowable PPV

$$du/dx_{allow} = (2\pi/\lambda) * u_{max\ allow} * \cos(2\pi n/\lambda) \text{ or}$$
$$= (2\pi/\lambda) * (PPV_{allow}/(2\pi f) * \cos(2\pi n/\lambda)$$

where n is the wave number or distance along the wave x, λ is the wave length and f is the dominant frequency of the ground motion. The procedure for these calculations is also described in the answer to problem 22-1 in Construction Vibrations (Dowding, 1996).

Figure 3 below shows that ½ of the relative rotation at the joint, Θ (=$\tan^{-1}$ du/dx), is equal to the difference in slope at the two ends of a pipe segment. This difference is the slope at the end of a segment that is located at the maximum ground motion displacement.

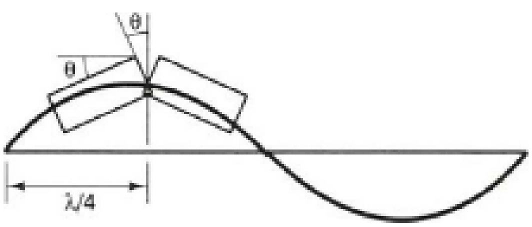

Figure 3 Relative joint rotation for a pipe segment as the maximum displacement of the ground motion passes by the joint.

Calculations based upon allowable joint rotational distortion show that allowable peak particle velocities (PPVs) exceed 366 mm/s or 14 in/sec for various segment lengths, propagation velocities and dominant vibratory frequencies.

Next consider limitation of PPV by limiting vibratory axial compressive stress in concrete pipe since its compressive strength, CS, is lower than DIP or PCV pipe.

$$PPV_{allow} = (CS/FS)*(c_p/E)$$

where FS is the factor of safety (3 in this case), PPV/c_p is the axial strain, c_p is the compressive wave propagation velocity and E is the modulus of elasticity of concrete. This concept is developed in Chapter 2 of Construction Vibrations

According to the American Concrete Pipe Association, concrete shall have a compressive strength of 31 Mpa (4500 psi) or greater (ACPA, 2018). A typical modulus of elasticity for concrete is 21 Mpa or 3,000,000 psi. The range of $c_{p,}$ which is approximately twice the shear wave propagation velocity, considered for this exercise is 2.5 to 5.5 m/s (8,000 to 18,000 ft/s). Lowest c_p will be chosen for the estimate of the allowable PPV as it will yield the lowest allowable PPV. Assuming that the concrete were substandard with a compressive strength of only 15 Mpa and that the pipe were in a weak rock with a low c_p of 1.25 m/s,

$$PPV_{allow} = (15/3)*(1.25/21) = 0.29 \text{ m/s} = 290 \text{ mm/s} = 11 \text{ ips}$$

The USBM RI 9523 Surface Mine Blasting Near Pressurized Transmission Pipelines introduced in Newsletter 20 included a 76 m long section of jointed PVC pipe that provides field verification of the robust nature of jointed PVC pipe. As described in Newsletter 20 this pipe had to be blown out of the ground to produce blast induced damage. In addition to measuring longitudinal strains on the pipe, it was filled with water and pressurized to 0.62 Mpa (90 psi) and monitored every 15 minutes as a measure of performance.

Despite sustaining PPV's of 240 mm/s (9.5 ips) on the ground above the pipe the internal water pressure was not lost, but did decline to 0.276 Mpa (40 psi) over the 6+ month duration of the project. This declination but not loss of pressure was described as "consistent with information that "O" ring water pipes such as this leak continuously".

Measurements of static or long-term settlement the PVC and other pipes were also made by the USBM. These measurements are helpful in assessing the importance of the allowable rotational joint distortion. They (Appendix C of RI 9523) indicate that the maximum elevation change between the ends and center of the jointed PVC pipeline (38m) was 7.6 mm. If it is assumed that this change occurred over just one 6 m long segment, $\Delta x/SL$ would be $7.6/(6*1000)$ or 0.0013 or an angle of 0.0726 degrees. This slope or angular rotation is less than $1/5^{th}$ the 0.007 $\Delta x/SL$ or 0.4 degrees allowed by WSSCWater during construction. Inclusion of these data should not interpreted to imply that these vibration levels induced vibratory densification of the clay backfill. As described in the RI, "clays are not particularly susceptible to vibratory densification and settlements and strains for vibrations below about 120 mm/s are small and irregular enough to be attributed to measurement scatter and normal settling-in". For instance the ends actually rose during imposition of PPVs up to 119 mm/s.

Whenever design PPVs near pipelines are high, the potential for the pipe to be in the crater zone of the blast is significant. No blasting should be allowed within the crater zone. Rare exceptions can be made with deliberate design and execution by a blaster with previous crater zone blasting experience. As described in Newsletter 24, when the pipe is in the crater zone of a potential blast, explosive gas pressure induced rock block movement becomes a major concern. A pipe will be in the crater zone whenever the nearest blast hole is within two, 2, blast-hole depths of the pipe as shown in Figure 4 in Newsletter 24.

References

WSSCWater (2021) (https://www.wsscwater.com/sites/default/files/sites/wssc/files/PDFs/W-12-2008_51036.pdf as of 29 Oct 2021). WSSCWater is a water and waste water supply agency for Montgomery and Prince Georges Counties, Maryland, USA, who maintain over 11,000 miles (18,000 km) of fresh water and sewer pipelines.

ACPA (2018) (http://www.concretepipe.org/wp-content/uploads/RCPStdPractice.pdf as of 29 Oct 2021) RCP Standard Practice Guide of the American Concrete Pipe Association.

INDOT (2014) Inspection Manual for Precast Concrete Pipe and Structures (https://www.in.gov/indot/doing-business-with indot/files/InspectionManualForPrecastConcretePipeAndStructures.pdf as of 29 Oct, 2021)