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Feasibility of state transportation agencies acquiring trenchless technologies: A comparison of open cut and horizontal auger boring

Lameck Onsarigo*, Simon Adamtey

College of Architecture and Environmental Design, Kent State University, Kent, OH, United States

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ABSTRACT

As State Departments of Transportation (DOTs) explore efficient and economical means to repair and replace culverts, trenchless technologies are increasingly becoming the method of choice. This is because trenchless technologies provide several advantages including eliminating or minimizing the risks and social costs of the traditional open-cut method. DOTs are also faced with the option of using their in-house crew or a specialty contractor. The choice between contractor and in-house crew is considered during the value engineering process. When using their own crew, the DOT may elect to use open cut or an applicable trenchless technology. However, state DOTs have a scope and dollar limit above which they must award a project through competitive bidding. It is therefore important for DOT's to determine if there is an adequate number of projects below this limit and scope to maximize the utilization of the equipment. Culvert installations completed by ODOT's own crew using an acquired horizontal auger boring (HAB) machine and the open-cut method were observed, and data collected. The research analyzed the direct costs and social costs for both HAB and open cut, and the payback for the acquired HAB system. The findings in this study indicate that the HAB technique is an economical alternative over open cut for replacement of culverts with depth of cover exceeding three feet. The findings also show that both HAB and open cut had a negative impact on the traveling public during construction; however, the impact of open cut was considerably higher. This paper can serve as a platform for other agencies to determine if it makes economic sense for them to acquire trenchless technologies.

1. Introduction

State departments of transportation (DOTs) are responsible for many culverts, which are important drainage structures under roads. The main purpose of these culverts is to transport fluid from one side of the highway to the other. As these culverts age and deteriorate, they will have to be replaced or rehabilitated to continue performance of intended functions and meet future demands. The rehabilitation and replacement of culverts can be costly, and the selection of the appropriate construction alternative is critical as these agencies strive to provide the most cost-effective and efficient service.

The traditional method of repair and rehabilitation of these underground drainage structures is to open cut the road, which includes excavating the deteriorated pipe and replacing it with a new one of equal or larger diameter. This method is expensive, especially in deep excavations, due to the need for shoring and dewatering. Apart from the direct cost of open cut, there are social costs associated with it. These include traffic disruption, road closures, business interruptions, noise pollution, environmental impact, and reduced safety for both workers and road users. Excavation can damage buried nearby utility lines such as gas, wastewater, and water lines, which can halt the replacement process. These concerns have necessitated innovative and alternative rehabilitation and replacement methods known as trenchless technologies that eliminate or minimize many of the risks and social costs of the conventional open-cut construction method. In favorable conditions, trenchless technologies are known to be less expensive than open cut (PPI, 2012). DOTs in states including Ohio, Iowa, Wisconsin, Indiana, Missouri, and Virginia, have taken a keen interest in exploring and harnessing the advantages of these trenchless technologies (Burden and Hoppe, 2015, Abraham et al., 2002, Salem, et al., 2008, Najafi et al., 2008).

During the value engineering phase of a project, it is equally important to determine if the construction work should be contracted or done by the in-house crew. When done in-house, the DOT may elect to use open cut or an applicable trenchless technology (in this case horizontal auger boring). State DOTs have a scope and dollar limit above which they must award a project through competitive bidding. Per the Ohio Revised Code (ORC) 5517.02 (B) (2), the force account limit for a

* Corresponding author.
E-mail addresses: lonsarig@kent.edu (L. Onsarigo), sadamtey@kent.edu (S. Adamtey).

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single project was $60,420 for the 2016/2017 fiscal year (ODOT, 2016). However, according to Lawriter LLC (2018), "on the first day of July of every odd-numbered year, the director can increase this limit by an amount not exceeding the lesser of three per cent, or the percentage amount of any increase in the department of transportation's construction cost index as annualized and totaled for the prior two calendar years." Within this force account limits, ODOT can rehabilitate or replace culverts using its own maintenance crew.

ODOT acquired a horizontal auger boring (HAB) machine in 2014 for in-house use as part of a research project. This presented an excellent opportunity for comparing costs for open cut and HAB installations when the work is done by the same/similar crew. The research team observed and collected data on culvert installations completed using the HAB machine by ODOT's crew as well as culvert installations completed using the open-cut method of installation by a similar crew. This study compares the cost of culverts installed using HAB to those installed using the open-cut method when the work is done by ODOT's workforce. The study includes an analysis of the payback period for the acquired HAB system and a comparison of the road-user delays (for both passenger cars and trucks) when HAB and open-cut construction methods are used to replace culverts.

2. ODOT's culvert condition rating

The ODOT culvert management manual requires inspection of culverts on a routine basis. These culverts are typically inspected for deterioration to barrel material or footing, cracks, dents and localized damage. The culvert condition is then determined based on the severity of these defects and the level of deterioration. There are nine different categories: excellent, very good, good, satisfactory, fair, poor, serious, critical imminent failure, and failed (ODOT, 2003). Culvers categorized as being in poor, serious, critical, imminent failure, and failed conditions need to be rehabilitated or replaced. ODOT (2003) defines these conditions as follows:

- Poor: corrugated metal pipes (CMP's) in poor condition have extensive heavy rust; thick and scaling rust throughout pipe; deep pitting; perforations throughout invert with an area less than 30 square inches per square foot, 20%. Overall the metal is thin, which allows for an easy puncture with a chipping hammer.
- Serious: CMP's in serious condition also have extensive heavy rust; thick and scaling rust throughout pipe; deep pitting. Perforations throughout invert with an area less than 36 square inches per square foot, 25%. Overall thin metal, which allows for an easy puncture with chipping hammer. End section corroded away
- Critical: CMP's in critical condition have perforations throughout the invert with an area greater than 36 square inches per square foot, 25%.
- Imminent failure: culverts in this condition have partially collapsed.
- Failed: culverts in this condition have undergone total collapse or total failure.

3. Culvert installation methods

Culverts can be installed using the open-cut method or one of the applicable trenchless technologies. The decision on which method to use (open cut or a trenchless alternative) should be based on an analysis of direct, indirect and social costs of the competing alternatives. Direct cost is the cost of furnishing the labor, material, and equipment needed for the construction job. The indirect cost includes the project overhead, mark up, design cost, bidding cost, supervision cost, etc. Social costs are the costs to the tax payer that are not included in bid price and include: road damage, damage to adjacent utilities, damage to adjacent structures, noise and vibration, pollution, vehicular traffic disruption, pedestrian safety, business and trade loss, damage to detour roads, site safety, citizen complaints, and environmental impacts. Vehicular traffic disruption is perhaps the most critical of these social costs (Gangavarapu et al., 2003, Bush and Simonson, 2001). This research focused on the use of horizontal auger boring (HAB) because ODOT purchased an auger boring machine for its in-house use. This presented an opportunity for comparing the two methods when construction is performed by the same/similar crews.

3.1. Open cut

Open cut is currently the most common method for underground utility construction because of its basic approach of digging a trench, placing a pipe in the trench, and filling the excavation (Woodroffe and Ariaratnam, 2008). It gets more complicated when unstable ground conditions are encountered, necessitating shoring, or when ground water is encountered, necessitating dewatering to lower the ground water table below the excavation subgrade. In locations where surface damage is not an issue, there is no ground water, and the ground is not congested with utilities, open-cut construction is usually the most cost-effective way to install a pipe (Onsarigo, 2014).

Traditional open-cut construction involves the following activities: exploring existing utilities, diverting traffic, excavation and shoring, dewatering, laying the pipe, backfilling, and restoring the site. For culvert installations under existing pavements, the activities would also include: saw cutting of the pavement; installation of temporary pavement; and repair/replacement of curb and sidewalk (City of Portland, 2015). In cases where the groundwater table is above the subgrade, dewatering becomes a necessity for the open-cut method. There are different dewatering systems that can be used including sump pumping, well-point system, and deep wells. A dewatering plan must be formulated to help effectively remove the water to permit work in a dry and safe trench. The treatment of the water in compliance with the environmental protection agency's (EPA) requirements is critical (CUIRE, 2004) and, if required, authorization to discharge the flow must be obtained prior to dewatering.

When excavations have the potential to endanger lives or adjacent properties, bracing to support the soil must be designed to meet OSHA (Occupational Safety and Health Act) requirements. OSHA recognizes depths exceeding five feet as surpassing the safety threshold and requires all trenches exceeding five feet in depth to be shored (OSHA, 2016). Some of the available shoring systems include sheeting and bracing, soldier beam and lagging, and trench boxes. In large construction areas, excavation walls may be sloped instead of providing structural support (Nemati, 2007). For rail and road crossings, sloping would mean ripping a bigger portion of the existing road, which increases the restoration costs and inconvenience, tremendously.

The traditional open-cut method can be used to install pipes of all materials and sizes. For shallow excavations above the groundwater table, open cut is usually the preferred alternative (IPBA, 2012). However, the method has a considerably higher negative impact on the environment and the community than trenchless technologies (Simicevic and Sterling, 2001). Massive excavations, the potential need to dispose of the excavated material at an off-site location, and the need to transport backfilling material to the site can cause significant disturbance to traffic, environment, local businesses, and residents, especially in urban areas (Salem et al., 2008).

3.2. Horizontal auger boring

Horizontal Auger Boring (also called the jack and bore method) is a technique for forming a cased horizontal bore through the ground, from a drive shaft to a reception shaft, by means of a rotating cutterhead. A rotating cutterhead at the front of the casing is attached to the leading end of an auger string. Spoil is transported back to the drive shaft by the rotation of helical-wound auger flights within the steel casing (ISTT, 2018). Vertical control, using a water level, is typical (Iseley and Gokhale, 1997). Fig. 1 is a picture of a HAB machine in a launch pit.

Fig. 1. Setup of the auger boring machine.

An auger boring system consists of the base push unit, casing pusher and casing adapters, power pack, auger sections, track, track extensions, saddle and saddle adapters, and cutterheads for different subsurface conditions. While the HAB method is generally used to install steel casing pipe in relatively soft and stable soil conditions such as clay, silt, and sand, today's cutterhead technologies have made it possible to install casings in some rock conditions above the water table (ASCE, 2017).

The auger boring process begins with advancing a steel casing into the ground with the cutterhead at the front of the lead casing. The cutterhead is rotated, cutting the soil at the face and directing the excavated soil to the augers inside the casing. The rotating augers transport the excavated material through the casing from the back end of the cutterhead to the jacking pit, where it is expelled via spoils ejector paddles through a trap door on the master casing pusher. After the lead casing is fully advanced into the soil, another casing (with the augers inserted in it) is placed on the track. The augers inside the casing are connected to the ones inside the lead casing. The two pipes are welded together, and the boring process is resumed by jacking the casings while simultaneously rotating the cutterhead and transporting the spoils to the jacking pit. This process is repeated until the cutterhead reaches the exit pit. The cutterhead is then disconnected, the augers withdrawn from the casing, and then the pipe is cleaned. If the casing is intended to be the carrier pipe, the pipe is ready to be used. Otherwise, a carrier pipe is inserted into the casing and adjusted for the designed grade, then the annular space between the casing and the carrier pipe may be filled with sand or grout or, in some cases, it may remain unfilled and both ends of the casing sealed with a bulkhead that may be vented to the ground surface. (ASCE, 2017).

3.2.1. Capabilities and limitations of horizontal auger boring

Some of the capabilities of the HAB method are:

- The method is typically used to install casings ranging from 100 to 400-foot-long; and diameters ranging from four inches to more than 72 in. (CUIRE, 2004).
- Typically, the method can achieve a vertical accuracy of up to ± 1 percent of the bore length (ASCE, 2017).
- The method is typically used for installation in soft soil (e.g., clay, silt, and sand) conditions (ASCE, 2017). Cutterheads fitted with tungsten carbide teeth, such as a Christmas tree cutterhead, can cut rock up to 4000 psi (28 MPa) (Long, 2006). Recent developments include cutterheads with disc cutters that enable HAB machines to excavate rock with an unconfined compressive strength (UCS) of 25,000 psi (170 MPa) and greater (Robbins Company, 2015).

Some of the limitations of the HAB method are:

- A carrier pipe and grouting of the annular space between the casing and carrier pipes may be needed if the soil is corrosive to the steel casing, which is an additional cost (ASCE, 2017).
- A size-specific cutterhead and auger flight (especially for the lead section) are required for each casing size which increases the initial investment cost of the equipment (ASCE, 2017).
- Cobbles and boulders can be problematic, but the HAB machine can work in such conditions if the cobbles and boulders are less than one third of the diameter of the casing (Najafi, 2013).
- The method is not suitable for boring through cohesionless soils under the ground water table (Najafi, 2013).

3.3. Horizontal auger boring vs open cut

Najafi and Kim (2004) conducted a comparison of the life-cycle-cost (LCC) of open-cut and trenchless pipeline construction. The paper presented an investigation of the cost-effectiveness of constructing underground pipelines with trenchless methods in urban centers relative to the cost of the conventional open-cut method. The analysis was qualitative, but it paved the way for more studies to calculate the "real" life-cycle-cost of construction projects so that design engineers and project owners can compare different alternatives and specify the most cost-effective and environmentally friendly methods. The study concluded that:

- material costs have a minor impact on the LCC of open-cut projects

and a major impact on the LCC of trenchless projects, and
- labor costs, indirect cost factors and social cost factors have a major impact on the LCC of open-cut projects, but they have a minor impact on the LCC of trenchless projects.

Gangavarapu et al. (2003) compared the traffic delays and costs involved during utility construction using open cut and auger boring. Case studies of two sites involving utility construction were considered in the study. They studied the auger boring technique and evaluated the construction factors that affect project productivity. The research utilized two simulation techniques to simulate the auger boring process and evaluate the productivity of auger boring systems. In the first case study that involved an installation crossing a street, the cost for open cut was $12,104.70 while that for auger boring was $9,219.50. The project consisted of a 12-inch gravity flow pipe, an 18-inch gravity flow pipe, and an 8-inch plastic cable conduit that were laid across a 30-foot wide road. HAB was cheaper in this case because of the high cost of traffic disruption associated with open cut when crossing the road.

The second case study involved the installation of a new pipeline parallel to the road. In this case the cost for open-cut installation was $4,524.00 while that for auger boring was $9,187.00. This second project involved the installation of a 12-inch diameter, 100-foot-long storm water pipe at a depth of five feet. In this case there was no significant difference in cost due to traffic disruption for both methods because the installation was not crossing the road. From these two cases, it is evident that the cost of traffic disruption contributed significantly to the cost of the project while using open cut when crossing a road.

Goduto and Atalah (2013) compared the design and construction costs of installing a 16-inch waterline underneath I-75 in Bowling Green, Ohio, using four potential alternatives: open cut with detouring traffic, postponing the installation until resurfacing the interstate to install the line by open cut, horizontal directional drilling, and auger boring. The study concluded that it could cost $604.50, $134.50, $57.47, and $173.44 per linear foot to install the pipe using horizontal auger boring, horizontal directional drilling, open cut with postponing the installation until resurfacing the interstate to install the line, and open cut with detouring traffic, respectively. This study did not compare actual construction costs but simulated costs for all construction methods using RSMeans. The study did not consider the social costs.

Other researchers have compared trenchless and open-cut methods when used for different applications. While the literature search conducted provided some insightful information on HAB and open cut, the comparisons were not specific to culvert installation. Furthermore, no literature comparing the costs of installing culverts using ODOT (or other DOT/agency) crews was found.

4. Research methodology

The research was completed in four phases.

The first phase was an analysis of ODOT's culvert database to determine the potential for the HAB machine utilization. The database obtained from ODOT contained records of culverts built from 1894 to 2014. Culverts that are good candidates for the HAB method met the following criteria:

(1) 24–48-inch diameter and length up to 120 feet (the size of the machine and accessories that ODOT acquired),
(2) Depth of cover greater than three feet (to avoid the risk of surface heave or subsidence),
(3) Culverts that have met/exceeded their design life. In this case, 50 years, which is generally the minimum specified (Gabriel, n.d.), and
(4) Culverts categorized by ODOT as being in poor, serious, critical, imminent failure, and failed conditions (ODOT, 2003). These culverts need to be rehabilitated/replaced immediately, or in the near future.

The second phase involved a cost analysis of culverts installed using HAB and open-cut methods by the ODOT crew. The ODOT crew installed five culverts (all ½-inch thick steel casings) using the acquired HAB machine over six months in 2014. The research team designed and planned these projects. The ODOT crew also installed four reinforced concrete culverts using the conventional open-cut method. The research team collected data from all the installations. The data collected from the observed installations included the duration of each activity, the resources (labor, materials, equipment) used to complete each activity, and the unit costs of these resources. Information on site conditions, sequence of activities, diameter and length of existing and replacement pipes, and ground conditions were also collected/observed and recorded. The direct and indirect cost for the HAB and open-cut installations were calculated and compared to determine the most economical method.

The third phase involved an analysis of the delay to road users from the construction work. The total delay to road users was calculated based on the average number of cars and trucks using the road, the duration of road closure, the length of the closed road, the normal speed limit on the road, and the reduced speed limit due to the construction work. The average annual daily traffic (AADT) data accessed through ODOT's Traffic Monitoring Management System (TMMS) was used as the average number of vehicles using the road. The duration of road closure and length of road closed were observed and recorded on site. During culvert installation using HAB, the road was completely open except when loading and offloading equipment and material (approximately one hour per day cumulatively). There was, however, a reduction in speed due to the construction work. For open-cut installations, there was either partial or complete road closure during construction. Total delay to road users was calculated for all HAB installations and compared to the simulated delay for same culverts assuming they were installed using open cut. See Appendix B for a table with the calculations of delays to road users for the HAB crossings. The observed and historical installations guided the open-cut simulations and two estimates were considered: (1) Estimate when only one lane was closed during the construction period, and (2) Estimate when the entire road was closed, and the nearest state route used as a detour.

The final phase of this research was an analysis of the payback period. The analysis of the payback period was conducted to determine how long it would take to pay back the initial cost of the acquired HAB machine. There is no profit in this setting, therefore the calculation is based on the average cost savings when using HAB over open cut. This analysis does not include social costs. The following assumptions were made in the analysis:

(1) The culverts installed were 100 feet long.
(2) Twelve (12) culvert installations per calendar year. The ODOT maintenance crew is involved in other works besides culvert installation. During the six months that that the ODOT crew was tracked, they installed five culverts using the HAB machine.
(3) The discount rate is assumed to be 3%. ODOT uses a range of discount rates (0 through 6) to see how the interest rate affects the apparent least-cost alternative (ODOT, 2008). The Federal Highway Administration (FHWA) also recommends using a discount rate ranging from three to five percent (FHWA, 2002). Three percent was considered a reasonable approximation following these two sources.
(4) Service life of six years for the HAB machine. Although the manufacturer's service life for the HAB machine goes beyond six years, to avoid additional estimation of the depreciation and salvage value, the service life was based on a similar HAB machine that was on sale after being in operation for six years. The current cost of this similar HAB machine then became the salvage value.

The cost of investment of the HAB machine, which includes the initial cost of \$243,381.07, annual maintenance cost of \$23,370.55 and salvage value after 6 years of \$161,000, was discounted using the present value (PV) function shown in Eq. (1).

$$= A\left(\frac{1-(1+i)^{-n}}{i}\right) + \frac{F}{(1+i)^n} \tag{1}$$

where P = discounted present cost, i = discount rate, n = number of years, A = annual cost, and F = future cost.

5. Results of analysis and findings

5.1. ODOT database analysis

The database included 84,000 culverts whose mean depth of cover was 4.7 feet. 7,839 culverts were found to be potential candidates for HAB because they met the following criteria: (1) 24–48-inch diameter and length up to 120 feet (the size of the acquired machine and its accessories), and (2) depth of cover greater than three feet.

The number of culverts that met the above criteria and were older than 50 years (i.e., outlived their design life) was 2713. It is important to note that about 30% of the culverts in the database have unknown age and some of them could have also exceeded their design life. The conditions (based on ODOT's culvert condition rating described in Section 2) of 153 of the 7839 culverts included serious (104), critical (19), imminent failure (5), and failed (25). There were also an additional 243 culverts in poor condition. All culverts with poor to failed condition appraisal are top priority for replacement.

5.2. Cost analysis

This analysis considered data from five observed HAB projects and four open-cut projects completed by the ODOT crews. Calculations of costs for HAB and open-cut culverts installed by the ODOT crew are presented in Appendix A. Table 1 is a summary of the five culverts installed by the ODOT crew using HAB. The cost per linear foot (Cost/LF) includes the following overhead rates: labor (80%), material (15%), and equipment (0%).

Table 2 presents the four open-cut projects that were installed by the ODOT crew. Similar to the HAB installation costs, the cost/LF includes the cost for labor, material, equipment, and overhead.

The research compared the costs for culverts installed using HAB to those installed using open cut. Fig. 2 presents the cost comparison between HAB and open cut for the 24-inch and 48-inch diameter culverts.

The average cost for the culverts replaced using HAB was lower than those performed using the open-cut method. There is a cost/LF difference of \$19 and \$140 for the 24 and 48-inch culverts, representing a cost savings of 10% and 25%, respectively.

5.3. Analysis of road user delays

The total passenger car-delay-hours ranged from 17-189 h per day for HAB, 79–882 h per day for the open cut with single lane closure and 172–1186 h per day for the open cut with road closed and traffic detoured. The total truck-delay-hours ranged from 4-10 h per day for HAB, 19–48 h per day for the open-cut method with single lane closure, and 9–176 h per day for the open-cut method with road closed and traffic detoured. Fig. 3 presents the average delay hours per day.

Vehicle-delay hours were considerably lower on HAB projects than on open-cut projects. Closing the road increased the travel distance for road users and increased traffic on the detour routes. Closing one lane created a bottleneck, which slowed down traffic and increased costs for the road users.

Table 1
Direct costs for HAB installations.

Label	Diameter (in.)	Length (ft.)	Depth of cover (ft.)	Cost/LF
HAB-I-1	24	100	12	\$ 173
HAB-I-2	24	120	12	\$ 149
HAB-I-3	48	60	3	\$ 411
HAB-I-4	48	50	3	\$ 432
HAB-I-5	24	130	14	\$ 205

Table 2
Direct costs for the open-cut installations.

Label	Diameter (in.)	Length (ft.)	Depth of cover (ft.)	Cost/LF
OC-I-1	24	100	5	\$ 120
OC-I-2	24	100	6	\$ 223
OC-I-3	24	120	8	\$ 243
OC-I-4	48	80	10	\$ 561

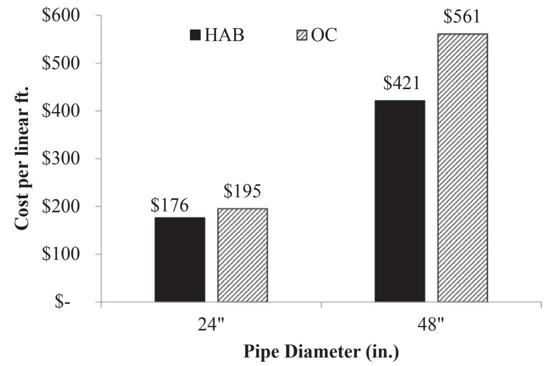

Fig. 2. Direct cost/LF comparison for horizontal auger boring (HAB) versus open cut (OC).

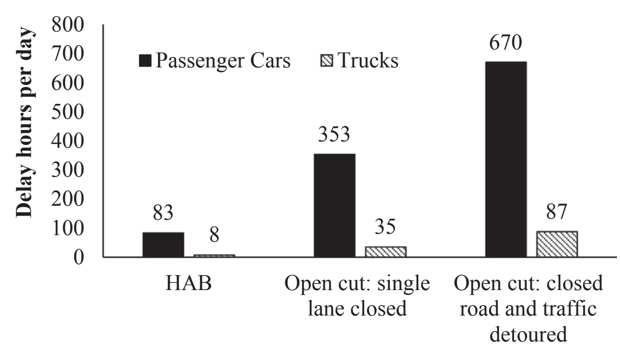

Fig. 3. Average delay hours per day.

5.4. Analysis of the payback period

From Fig. 2, there is a cost/LF difference of \$19 and \$140 for the 24 and 48-inch culverts, respectively. This reflects the cost savings when HAB is used in lieu of open cut. Over the project duration, the research team installed three 24-inch and two 48-inch culverts using HAB. The average cost savings from the five observed installations is \$67.40 per linear foot {(\$19 × 3 + \$140 × 2)/5}. Using Eq. (1), the discounted cost of investment was \$208,983.81. This cost was used in the calculation of the breakeven and payback period. The cash flow for year 1 to year 6 is \$80,880. This is based on the assumption that 12 culverts averaging 100 feet each are installed annually (67.40 × 12 × 100). The breakeven and payback analysis was conducted in Microsoft Excel as shown in Table 3 using the Net Present Value (NPV) function. The discounted cost of investment was deducted from the discounted cumulative savings for each year to determine the breakeven and hence

Table 3
Breakeven and payback period.

Year	Cash flow	Savings-Investment Cost
0	−$208,983.81	−$208,983.78
1	$80,880.00	−$130,459.54
2	$80,880.00	−$54,222.38
3	$80,880.00	$19,794.27
4	$80,880.00	$91,655.11
5	$80,880.00	$161,422.90
6	$80,880.00	$229,158.63

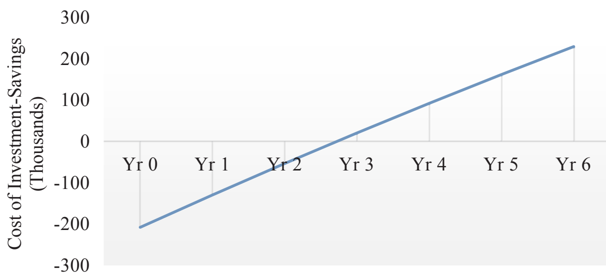

Fig. 4. Breakeven and payback period.

the payback period. The analysis indicated that the payback period is three years as shown in Fig. 4.

6. Discussion and conclusions

The HAB method offers several advantages when employed for the installation of culverts, including less traffic and environmental disruptions (Najafi, 2013). The findings in this study indicate that the HAB technique is an economical alternative over open cut for replacement of culverts with depth of cover exceeding three feet. This conclusion was based on a small number of comparable (diameter, depth, and length) installations. Although these culverts were randomly selected and they represent the types of culverts that ODOT manages, further studies are needed to identify a larger number of comparable culverts installed using open cut and HAB methods, to confirm and validate the above stated finding.

The findings in this comparison are in contrast to those presented in the literature review portion of this paper which concluded that open cut is a lower cost alternative. There are two potential reasons for this disparity.

(1) Contracted HAB crossings typically require monitoring and steering of the bore, which reduces the production rate thus increasing the cost. The observed ODOT installations were not monitored or steered.
(2) Costs for observed ODOT installations does not include markup. Markup rates for HAB installations are expected to be higher than open cut for the following reasons
   (a) Bid prices for HAB installations completed by a specialized subcontractor working under a general contractor usually include double mark ups.
   (b) High competition for open-cut work generally drives the cost of installation down while the significantly lower competition among HAB contractors leads to higher markup rates.

Both the HAB and the open-cut construction techniques had a negative impact on the traveling public during construction; however, the impact of open cut was considerably higher. In almost all the HAB installations, the road lanes were mostly open except during the loading and unloading of equipment and material, and occasionally when a piece of equipment required additional space. Open-cut installations demand partial or complete road closure, which increases travel distance, and/or travel time to the road users.

The payback period for the HAB machine acquired by ODOT is three years assuming the crew installs 12 culverts each year using the HAB machine. This conservative number (12 installations per year) was favored since the ODOT maintenance crew is involved in other maintenance activities. A crew solely dedicated to HAB work will install many more culverts in a year. Consequently, the payback period will be shorter than three years and more savings will be realized.

It can be concluded from the research that it is prudent and economical for DOTs to acquire HAB machines for in-house use. However, it is important for each DOT to ascertain that there are adequate number of culverts to maximize the utilization of the machine. From the analysis in this study, it would make economic sense for a DOT to acquire the machine if they anticipate a need for installing at least 12 culverts annually using HAB.

Further research is needed to investigate the viability of other trenchless technologies for replacing or renewing culverts. Under the right conditions, trenchless replacement and rehabilitation methods like horizontal directional drilling (HDD), pipe bursting, sliplining, cured-in-place-pipe (CIPP), spray applied systems, fold-and-form, and spiral-would pipe may prove to be more economical alternatives to the methods investigated here.

Declaration of Competing Interest

The authors declared that there is no conflict of interest.

Appendix A. Cost calculations for HAB and open cut

HAB in-house installations					
Project Code	HAB-I-1	HAB-I-2	HAB-I-3	HAB-I-4	HAB-I-5
County/ODOT District	Knox/D5	Knox/D5	Vinton/D10	Vinton/D10	Perry/D5
Location	KNO-62-2.10	KNO-62-2.20	VIN-50-18.25	VIN-160-7.15	PER-93-8.5
New pipe diameter (In)	24	24	48	48	24
Length (feet)	100	120	60	50	130
Depth of cover (feet)	12	12	3	3	14
Cost of labor	$ 3,384.51	$ 3,926.60	$ 4,927.73	$ 4,827.80	$ 7,245.51
Labor overhead	$ 2,707.61	$ 3,141.28	$ 3,942.18	$ 3,862.24	$ 5,796.41
Cost of equipment	$ 3,125.26	$ 3,561.24	$ 4,588.13	$ 3,501.69	$ 6,055.26
Equipment overhead	$ 0.00	$ 0.00	$ 0.00	$ 0.00	$ 0.00
Cost of materials	$ 7,052.26	$ 6,327.53	$ 9,731.40	$ 8,183.02	$ 6,592.90
Material overhead	$ 1,057.84	$ 949.13	$ 1,459.71	$ 1,227.45	$ 988.94
Total cost	$ 17,327.48	$ 17,905.78	$ 24,649.15	$ 21,602.20	$ 26,679.01
Cost/linear foot	$ 173.27	$ 149.21	$ 410.82	$ 432.04	$ 205.22

Open-cut in-house installations

Project Code	OC-I-1	OC-I-2	OC-I-3	OC-I-4
County/District	Gallia/D10	Guernsey/D5	Guernsey/D5	Perry/D5
Location	GAL-218-2.80	GUE-265-3.13	GUE-265-3.47	PER-312-3.28
Diameter (In)	24	24	24	48
Length (feet)	100	100	120	80
Depth (feet)	5	6	8	10
Cost of labor	$ 1,601	$ 5,379	$ 6,612	$ 13,947
Labor overhead	$ 3,682	$ 4,303	$ 5,290	$ 11,157
Cost of Equipment	$ 1,249	$ 1,417	$ 1,810	$ 2,733
Equipment overhead	$ 125	$ 0	$ 0	$ 0
Cost of Material	$ 3,997	$ 9,705	$ 13,435	$ 14,824
Material overhead	$ 1,359	$ 1,456	$ 2,015	$ 2,224
Total cost	$ 12,013	$ 22,260	$ 29,163	$ 44,885
Cost/linear foot	$ 120	$ 223	$ 243	$ 561

Appendix B Road user delay hours for the HAB crossings

HAB in-house installations

#	Location	Formula	HAB-I-1 KNO-62–2.10		HAB-I-2 KNO-62–2.20		HAB-I-3 VIN-50–18.25		HAB-I-4 VIN-160–7.15		HAB-I-5 PER-93–8.5	
			Passenger Cars	Trucks	Passenger Cars	Trucks	Passenger Cars	Trucks	Passenger Cars	Trucks	Passenger Cars	Trucks
	New pipe diameter		24		24		48		48		24	
	Length		100		120		60		50		130	
A	Length of Work zone in miles		**3**	**3**	**3**	**3**	**3**	**3**	**3**	**3**	**5.4**	**5.4**
B	Free flow speed (normal 85% speed) in mph		**55**	**55**	**55**	**55**	**55**	**55**	**55**	**55**	**50**	**50**
C	Work zone speed (85%) in mph		**40**	**40**	**40**	**40**	**40**	**40**	**40**	**40**	**35**	**35**
D	AADT of full section		**3370**	**500**	**3370**	**500**	**3050**	**410**	**830**	**200**	**2000**	**120**
E	Travel time in free flow (sec)	(A/B) *3600	196	196	196	196	196	196	196	196	389	389
F	Travel Time in work zone (sec)	(A/C) *3600	270	270	270	270	270	270	270	270	555	555
G	Delay (sec)	F-E	74	74	74	74	74	74	74	74	167	167
H	Delay (hours)	G/3600	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.05	0.05
I	Delay hours per day (all vehicles)	H*D	69	10	69	10	62	8	17	4	93	6

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