

## Power earth auger modification for waste extraction from pit latrines

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### ABSTRACT

The extraction auger was developed to meet the need for a low cost, effective method to empty pit latrines in difficult to access locations. The basic design consists of a motor that rotates an auger inside a pipe, lifting waste from a pit and depositing it into containers through a wye fitting at the top of the device. Laboratory testing of the auger showed increases in flow rates with increasing auger rotational speed and waste viscosity. An auger with an external hydraulic drive was capable of lifting dairy waste over 2.5 m, at flow rates of over 125 liters per minute. Field-testing showed the equipment was effective at lifting medium viscosity wastes containing a mixture of liquid and solid material. However, the auger was not effective in removing low viscosity, liquid waste that would flow backward down the auger reducing lifting efficiency. The auger was capable of drilling into dense solid waste, forming a 'posthole' in the waste. However, since the dense solid waste would not flow towards the auger intake, actual waste removal from the pit was limited. Improved methods are needed to mix liquid and solid waste in pits prior to removal with the extraction auger or other technologies.

**Key words** | auger, pit emptying, portable

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### INTRODUCTION

Pit latrines can provide improved sanitation at a relatively low cost, but require periodic emptying to remain effective. However, physically accessing the pits and removing the accumulated waste is a major challenge in many developing areas. Mechanical emptying equipment used in developed countries such as vacuum tankers cannot access pit latrines located far from paved roads and often only removes the liquid fraction, leaving dense solids in the pit which are difficult to remove. In the absence of an effective and economical alternative, many pits are emptied by manual laborers (manual extraction) exposing workers and the surrounding community to a variety of pathogens (Still & Foxon 2012).

Waste pit characteristics and their contents vary greatly, further complicating the emptying process. Pit volumes are reported to vary between 1 and 4 m<sup>3</sup> with typical depths

of up to 2 m (Mara 1984; Still 2002). 'Wet' pits containing a substantial amount of liquid material are reported to separate into three layers: floating scum, a liquid layer, and a sludge layer (Hawkins 1982) where the consolidated sludge layer is reported to have densities of up to 1,750 kg/m<sup>3</sup> (Radford 2011). However, Seal (2012) found that the contents of pits in Kibera, Nairobi were much more variable. While the contents of some pits were consistently soft and others consistently hard, some pits had multiple layers with hard layers sometimes overlying watery layers. 'Dry' or well-drained pits usually only contain the sludge layer and show a trend of decreasing moisture content from the surface of the pit to a 1 m depth and little to no change past that depth (Still & Foxon 2012). Waste accumulation rates can vary tremendously, with pit fill times ranging from 3 to 20 years (Still 2002). Fill rates vary depending on the

number of users, soil type and depth to water table, material used for anal cleansing, and the amount of rubbish (trash) added to the pit (Pickford 1995; Still 2002). In some countries, up to 20% of the pit contents may be solid waste (trash), which can cause major operational problems with many mechanical pit-emptying devices (Still 2002). Some pits are only accessible through the toilet hole inside the latrine superstructure or by drilling holes in the side of the latrine, further complicating the emptying process (Still 2002).

A variety of devices have been developed to aid in pit emptying. Manual extraction tools include buckets, shovels, and specialized scoops that allow laborers to remove the waste without having to physically enter the pit. Pumping systems include: (a) traditional diaphragm pumps; and (b) the Gulper, a hand powered pump that draws waste through a foot-valve submerged in waste, forcing it up a solid pipe through a wye fitting and into a collection device (Ideas at Work 2010). Mechanical and manual pumps can effectively remove liquid wastes, but are prone to clogging, have increased wear due to the direct contact between the waste and mechanical components, and cannot pump dense or dry sludge (Thye *et al.* 2011). Vacuum systems include: (a) traditional vacuum trucks; (b) smaller, more maneuverable mechanized vacuum systems including the Microvac (Jere *et al.* 1996), Dung Beetle (Tucker 2010), and Vacutug (Wegelin-Schuringa & Coffey 2000); (c) the MAPET system, a hand powered piston pump and tank mounted on a small pushcart (Muller & Rijnsburger 1994); and (d) the eVac, a lightweight vacuum system powered by gasoline or electric motors that deposit the waste directly into 47-liter plastic containers for off-site transport (Still & O’Riordan 2012). Important advantages of vacuum systems include: (a) reduced wear and clogging of mechanical equipment by direct contact with the waste; and (b) reduced contact with waste, odors and fly nuisance (as long as the pipes remain unblocked). However, many vacuum systems cannot extract waste from more than 0.8 m below the ground surface and have difficulty removing dense and/or dry sludge (O’Riordan 2009; Thye *et al.* 2011; Still & Foxon 2012; Still & O’Riordan 2012).

In this work, we report on the development and testing of a screw auger inside a pipe to extract waste from pits and deposit the waste into containers for off-site transport. Still

& O’Riordan (2012) described the development of an electric motor powered screw auger for waste removal from pits, but reported problems include: (a) difficulty in transporting, maneuvering, and cleaning the auger due to the large size and weight of the equipment; (b) clogging with rubbish in the pit; and (c) difficulty with use in shallow or deep pits or inside a toilet superstructure because of the fixed size of the equipment.

Based on the work of Still & O’Riordan (2012) and others, the following performance criteria were developed for the proposed extraction auger.

- (a) Hydraulic performance: The auger should be capable of lifting 40 liters per minute (Lpm) of semi-solid sludge 2–3 m allowing a typical 2–4 m<sup>3</sup> pit to be emptied in 1–2 h.
- (b) Portable and maneuverable: The auger should weigh less than 50 kg allowing hand transport by two laborers to remote pit locations. Once inserted into the pit, the auger should be easily maneuverable by one operator while a second person directs the waste into containers for off-site transport.
- (c) Simple and durable: The auger should be simple to operate and maintain using locally available materials and labor. The auger should be sufficiently durable for daily use with little maintenance, and should be capable of lifting waste containing some rubbish without damage to the device.
- (d) Sanitary: The auger should allow safe and effective emptying of pit latrines while providing for hygienic separation of waste. This consideration includes equipment transport, assembly, waste transfer from the pit into the transport containers, equipment cleanup and removal from the site. If rubbish does get caught inside the auger, the device should allow simple and hygienic removal of the trash.
- (e) Manufacture: Ideally, it should be possible to manufacture the auger using locally available materials.

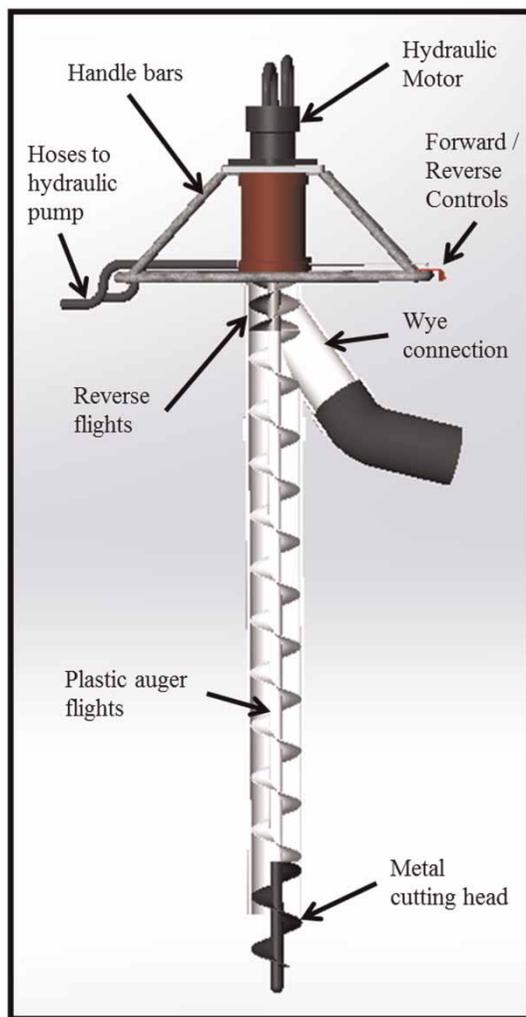
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## EXTRACTION AUGER DESIGN

The extraction auger described here was developed through a process of design, fabrication and testing, followed by redesign and additional testing. The design described below

meets many of the criteria presented above, and provides the basis for further development of effective pit emptying technologies.

The basic design consists of a continuous flight auger that rotates inside a pipe, transporting waste upward, before discharging through a 45° wye fitting into containers for off-site transport (Figure 1). In our final design, the auger is rotated by a hydraulic motor that provides high power and is easily reversible to discharge debris that enters the auger. The hydraulic motor is powered by a remotely located gasoline driven hydraulic pump.



**Figure 1** | Final extraction auger design with pipe cut-away view showing metal cutting head, plastic auger flights to transport waste inside plastic pipe, wye discharge connection, reverse flights at top of auger to aid in waste discharge, hydraulic motor, handle bars and controls. External gasoline-driven hydraulic pump not shown.

The main body of the extraction auger consists of a straight section of high-density polyethylene (HDPE) auger flights (9.5-cm outer dia.) mounted on a 2.5 cm dia. stainless steel hex center shaft (Lundell Plastics Corp., Odebolt, IA). The HDPE flights are enclosed in 10 cm nominal dia. schedule 40 polyvinyl chloride (PVC) pipe. The top end of the PVC pipe is glued to a 10 cm × 10 cm × 10 cm PVC wye fitting. Waste moves upward through the auger to the wye, turns 270°, and discharges out the wye through a collapsible 10-cm PVC hose. A handle attached to the discharge end of the collapsible hose assists in directing the waste into a suitable collection container.

At the bottom (intake end) of the auger, two flights of steel auger extend past the end of the PVC pipe to convey waste into the solid pipe portion of the auger. Steel replaces the HDPE in this section to improve the durability of the exposed flights. A 2.5 cm dia. steel ball can be welded to the tip of the steel auger to prevent the auger from damaging the bottom of the pit, if desired. The length of the extraction auger can be increased to empty deeper pits by attaching 30, 60 or 90 cm lengths of HDPE auger and PVC pipe.

Inside the wye at the top of the screw, there is a 20 cm long section of double helix reverse flights to aid in discharging the solids through the wye into a collection container. Field testing showed the reverse flights and wye are needed to prevent accumulation of compacted material inside the upper portion of the auger. In the current version, the reverse flights are manufactured from welded steel plate. However, weight could be reduced by replacing the reversed steel flights with HDPE or other lightweight material.

The auger and wye fitting are connected to the hydraulic motor using a fabricated coupling machined from 15-cm diameter nylon round stock. The top 5 cm of the PVC wye fitting slides into the coupling to provide a secure fit and is held in place by four cap screws. A fabricated steel shaft passes through the fabricated coupling, connecting the output shaft of the hydraulic motor to the auger.

The hydraulic motor used in our design is an Eaton Char-Lynn model 103-1,034 (75 cm<sup>3</sup> per rotation displacement) and is rated for continuous operation at 493 revolutions per minute (rpm), providing a torque of 148 Nm at a flow of 38 Lpm and maximum pressure of 138 bar. Hydraulic power to drive the motor is supplied by a 10.7 HP Honda GX340 gasoline engine (Little Beaver

Inc., Livingston, TX). Hydraulic fluid is transferred from the hydraulic pump to the hydraulic motor through 7.6 m lengths of hydraulic hoses with quick-connect fittings. The hydraulic motor, forward and reverse controls, pressure gage and extraction auger are mounted to a handle bar frame constructed from 1.9-cm steel pipe. Total assembled weight of a 2.7 m long unit is 48 kg excluding hydraulic pump and hoses.

## LABORATORY TESTING

The hydraulic performance of the auger was first evaluated in the laboratory using a bentonite slurry to simulate fecal waste by monitoring pumping rate and discharge pressure while varying auger rotational speed (100, 200, 300, 400 and 500 rpm), auger submergence, and slurry viscosity. For these initial tests, the auger was driven by a 1 HP electric motor with a rheostat to control the auger rotational speed. The motor was attached to a metal stand that held the prototype vertical and allowed for different height settings (Figure 2). All tests were conducted with the auger

oriented vertically, when auger performance was expected to be lowest (Roberts 1964; Dixon & Humphries 1995). In all of the laboratory tests, a 1.5 m long auger was used with a 10 cm × 10 cm × 5 cm tee fitting outlet. Clear manometer tubes were attached to the sides of the auger at four locations to examine the change in head produced over the length of the auger. Auger speed was monitored with a laser tachometer. The auger discharge rate was measured using a stopwatch and a 19 L pail.

For the initial testing phase, a simulated waste was prepared from high yield bentonite clay and water. Mixtures of 5, 6, and 7% by weight bentonite were used to generate shear thinning materials with effective viscosity varying from 0.3 to 700 Pascal-seconds (Pa-s) resulting in shear rates of 0.2 and 21 L/second (L/s), with higher bentonite concentrations yielding higher viscosities (Rogers 2013). Advantages of the bentonite mixtures include: (a) thixotropic properties that are similar to human waste; (b) absence of pathogens; and (c) biological stability, allowing testing over extended periods in the laboratory.

Figure 3 shows the variation in flow rate for three different solids contents and two different submergences (intake

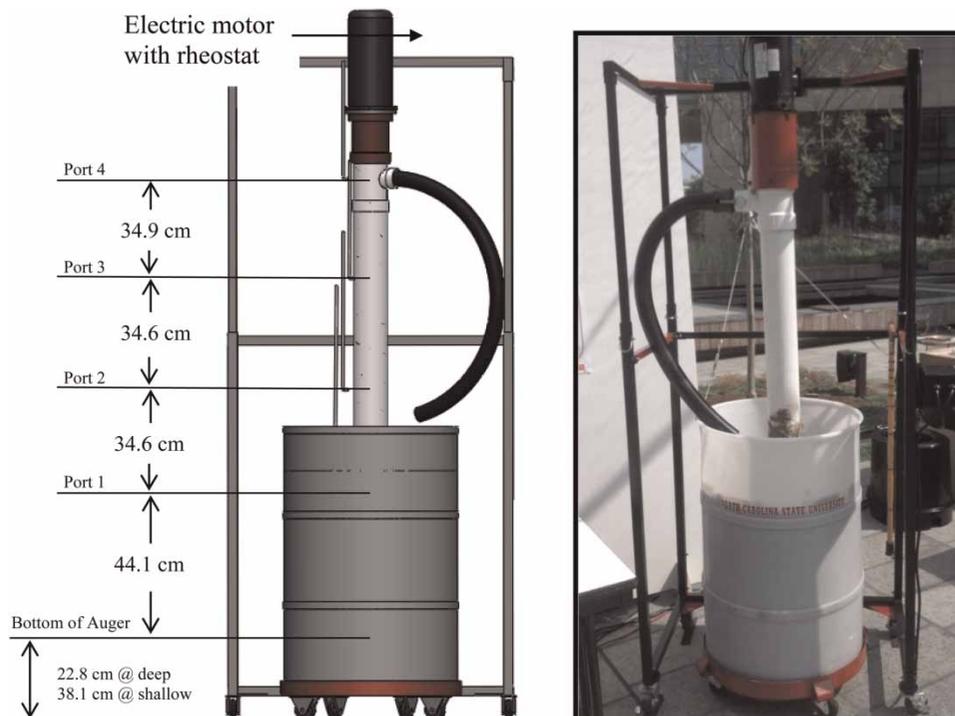
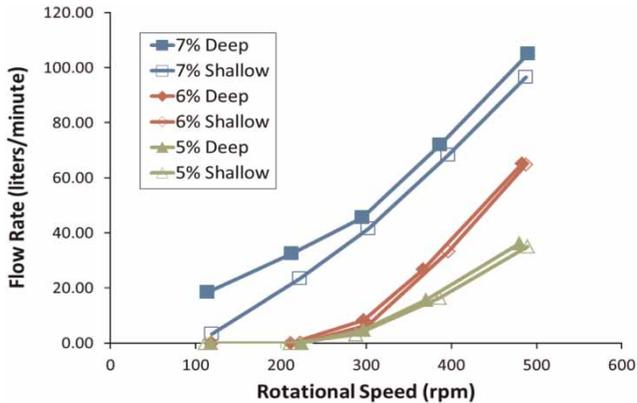


Figure 2 | Experimental setup diagram for extraction auger.



**Figure 3** | Flow rate vs. auger rotational speed for 1.5 m long × 10 cm diameter auger for shallow (30 cm submergence) and deep (45 cm submergence) settings with 5 cm of exposed auger and 5, 6 and 7% bentonite mixtures.

30 and 45 cm below sludge level) with 5 cm of auger extending beyond the pipe end. Auger rotational speed and waste viscosity had a major impact on the flow produced with a speed of over 200 rpm required to pump the less viscous 5 and 6% material. In contrast, the more viscous 7% mixture could easily be pumped at 200 rpm. A pumping rate of at least 40 Lpm is required to empty a typical pit of 2–4 m<sup>3</sup> in 1–2 h, which would require a rotational speed of at least 300 rpm. Typical direct drive earth augers have maximum speeds of 180–250 rpm, indicating standard ‘off-the-shelf’ augers may not be appropriate for pit emptying applications.

The discharge pressure generated by the auger increased with rotational speed, but was low for all conditions tested (maximum pressure head produced = 14 cm) indicating: (a) the auger will not generate sufficient pressure to pump material through any significant length of hose; and (b) the auger will need to extend above the collection container and discharge by gravity into the container.

Changes in intake submergence had minimal impact on flow rates for the 5 and 6% bentonite mixtures, suggesting that flow of low viscosity materials into the auger intake was not rate limiting. However, for the more viscous 7% bentonite mixture, the smaller intake submergence did result in a reduction in pumping rate. An increase in length of exposed auger beyond the pipe intake (choke length) had minimal impact on flow rate for the lower viscosity materials, but resulted in a small increase in flow for the highest viscosity material (data not shown). These results suggest that flow into the auger intake can be rate

limiting for more viscous materials, especially as the pits are emptied, reducing auger submergence. Field-testing of a similar screw conveyor in South Africa found the flow rate to decrease by 80% as the pit neared empty (Still & O’Riordan 2012).

In a series of papers, Roberts (1964, 1999, 2001) developed relationships to describe transport of non-cohesive, granular material in screw conveyors. Screw conveyor efficiency is a function of the fill efficiency and vortex efficiency. For materials with a high friction coefficient, conveyance is limited by the rate that material enters the screw conveyor intake (fill efficiency). However, for materials with a low friction coefficient, conveyance is limited by backwards flow through the screw, especially when the conveyor is oriented vertically. Roberts’ work indicates that conveyance will be zero at low rotational speeds when the vortex efficiency is negative. As the friction coefficient increases, less rotational speed is required to achieve flow.

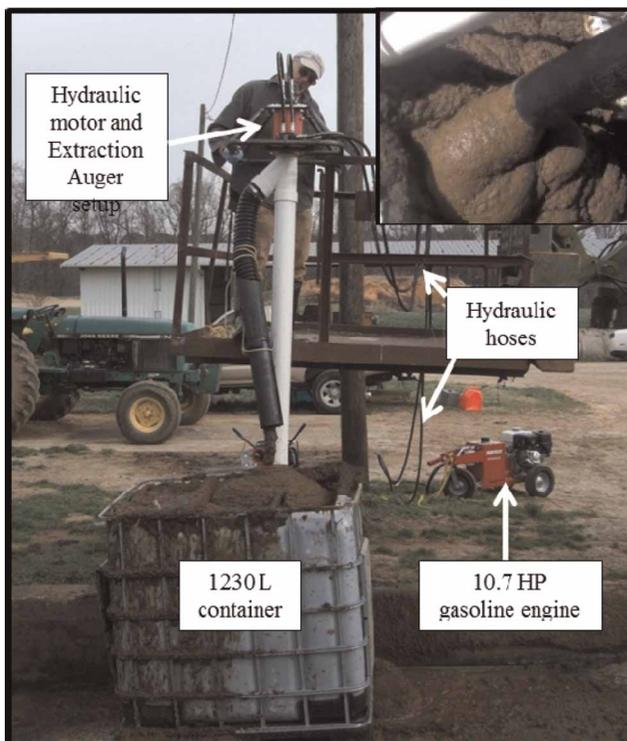
While the relationships developed by Roberts (1964, 2001) for predicting conveyance of non-cohesive granular materials are not directly applicable to the cohesive, thixotropic bentonite mixtures, the experimental results we obtained were generally consistent with his approach. For low viscosity mixtures (analogous to materials with a low friction angle), flow was zero for low rotational speeds. As the bentonite viscosity increased (analogous to materials with a higher friction angle), lower rotational speeds were sufficient to generate flow. In our testing, the auger achieved a maximum volumetric efficiency of 26%, which is also generally consistent with Roberts’ work. This relatively low efficiency is due to the vertical orientation of the auger, which increases the slip of material backwards through the auger (Roberts 1964). Pumping efficiency increases significantly if the auger is placed at an angle, reducing backwards flow through the auger.

## ANIMAL WASTE TESTING

Following the laboratory testing and a series of initial field tests to refine the equipment, the hydraulic motor-powered auger design described above was tested on waste from the dairy cattle barns at the North Carolina State University

Lake Wheeler Farm. The test material consisted of a mixture of cow manure and a small amount of sand or wood shavings that was washed out of the dairy barns and collected into a settling basin. This material had a moisture content of 80.9%, organic content of 9.7%, inorganic content of 9.5% and contained solid particles (wood shavings) up to 1 cm in length. The waste moisture content of the waste is within the range of moisture contents reported for fresh human feces (Still & Foxon 2012). Figure 4 shows field testing of a 2.7 m long unit with a 15 cm choke length to pump dairy waste out of a 1 cubic meter container with a 36 cm × 90 cm opening on the top. The extraction auger is being operated from a lift to simulate pumping waste out of the bottom of 2 m deep pit latrine.

When the auger was first used with dairy waste, there were repeated problems with jamming of the auger as small pieces of wood shavings became lodged between the outside edge of the auger flights and the pipe interior. While the wood shavings could be easily dislodged by reversing the auger for 1 to 2 seconds, this reduced productivity.



**Figure 4** | Extraction auger being used to pump dairy waste 2 m upward from a 1 m<sup>3</sup> container.

To resolve this problem, the outside diameter of the HDPE auger flights were reduced slightly, increasing the gap between the flights and the pipe to 3.2 mm from 0.8 mm. This change greatly reduced jamming, increased rotational speed from 380 to 410 rpm, and reduced the hydraulic pressure required to drive the auger from 12.4 to 8.3 MPa, but did result in a small reduction in flow. Roberts (1999) suggests a clearance of between 1.5 and 3 times larger than the maximum particle size to prevent jamming and energy loss as well as limiting slip back and a loss of efficiency.

Lockup or jamming of the auger was also reduced by increasing the maximum hydraulic pressure (controlled by a pressure relief valve) from 10.3 to 13.8 MPa. The increased torque provided by the higher pressure was able to dislodge most material without locking up the auger. When the auger did jam, the hydraulic controls on the handle bar allowed the auger rotation to be easily reversed and dislodge any trapped material. In all cases, a 1–2 second reversal of the auger was effective in dislodging trapped material. This allowed continued pumping of the waste without any other action.

The final design generated a flow rate of 127 Lpm when dairy waste was lifted 2 m out of the bottom of a 1 m deep waste container. However, flow declined to 88 Lpm as the waste container was emptied with the lift increasing from 2.0 to 2.35 m and intake submergence decreasing from 0.7 to 0.35 m. As waste level in the tank declined below the pipe intake, a second person would need to push the waste towards the auger intake with a shovel to continue pumping. In practice, this may not be necessary since it can be beneficial to leave a small amount of waste in the bottom of the pit, enhancing degradation of future waste (Still & O’Riordan 2012).

## FIELD TESTING

Over a four-day period in March 2013, our modified design was tested on a total of six pit latrines in South Africa. The hydraulic powered extraction auger was easily carried to all of the pits investigated. While it was not possible to drive a vehicle close to many latrines, access with the equipment was not a problem. Overall, the machine was effective at



**Figure 5** | Extraction auger being used to empty pit latrine in Durban, South Africa.

pumping medium viscosity wastes containing a mixture of liquid and solid material. **Figure 5** shows the pumping operation. Five 75-liter containers were pumped out over about 20 minutes of operation.

In general, clogging with trash and other debris was not a problem. Reversing the auger ejected most debris. While elastic bands (presumably from disposable diapers) did occasionally get wrapped around the auger, they did not result in jamming of the equipment. When trash was caught in the auger, the machine could be easily reversed, ejecting most of the trash and other debris.

The major operational limitation with the auger was associated with extracting either very low or very high viscosity waste. As shown during the initial laboratory testing, the auger is not efficient for pumping watery, low viscosity waste, and other available technologies (Gulper, Vacutug or a simple trash pump) are more effective. The equipment was also not effective in removing solid waste in dry pits without some liquid to allow the material to flow to the auger intake. The auger was able to drill into high solids waste, forming a ‘posthole’ in the non-flowing solid waste. Problems were also encountered in pits with a

dry layer floating on top of liquid waste. The current design could penetrate the dry floating layer, but was not effective in mixing the wet and dry material to generate a pumpable slurry.

Additional work is needed to develop effective methods to empty pits containing solid material that does not flow into the auger intake. Potential solutions include development of equipment that could mix the liquid and solid material followed by pumping using the extraction auger and/or vacuum equipment. Additional needs include: (a) development of methods to determine the amount and character of waste through the toilet hole, prior to breaking the pit seal; and (b) standardized sanitation protocols to reduce the spread of waste and fecal borne pathogens during pit emptying.

## CONCLUSIONS AND RECOMMENDATIONS

A relatively simple, low cost extraction auger was developed to remove semi-solid sludge from waste pits. The current design is capable of lifting dairy waste over 2.5 m at flow

rates of 125 Lpm, allowing typical waste pits to be emptied in 1–2 hours. A rotational speed of at least 350 rpm is needed to lift less viscous, ‘water-like’ wastes. The auger produces minimal pressure at the discharge end so the waste must be discharged directly into another container for off-site transport. In general, jamming or clogging with trash and other debris is not a major problem.

The current design can be easily transported and used by two men. A 2.7 m long unit weighs 48 kg and can provide adequate flow while still being maneuverable with one or two operators. Wrap-around handlebars and a support stand allow reasonably easy operation by one person. Use of an external hydraulic drive significantly reduced the weight, while providing sufficient power. The extraction auger can be assembled inside a latrine structure using several shorter lengths of auger and pipe. However, this is cumbersome and can increase the risk of waste spillage during disassembly after the pit has been emptied. The unit is also somewhat difficult to maneuver in pits full of waste, so further reductions in weight would be beneficial.

The reverse mechanism allows waste remaining inside the auger to be discharged back into the pit, reducing the equipment weight and waste spillage outside the pit. A rubber squeegee with a long handle allows the operator to wipe down the outside of the pipe during emptying, further reducing spillage. Between pits, the auger inlet and outlet can be capped to minimize exposure to the waste and reduce the time spent cleaning the equipment. When the auger needs to be disassembled, flushing a steady stream of water through the outlet while running the mechanism in reverse is effective in removing most waste. However, further work is needed to develop better cleaning methods as there is an ongoing risk of waste spillage during the emptying process and associated human exposure.

In general, the auger was reasonably durable and there was little evidence of damage during routine operation. Field-testing showed some scoring of the inside of the PVC pipe casing and some feathering deterioration of the edge of the HDPE auger. On one occasion, a small piece of pipe at the auger intake broke off, presumably due to material wedging between the inlet of the pipe and the edge of auger flights. A 20 cm section of metal auger was used at the end of the HDPE auger to reduce exposure of the weaker HDPE material. A short section of metal pipe could also be

added to the auger inlet to reduce damage to the inlet of the PVC pipe. Further modifications may be needed to allow manufacture using locally available materials.

The most critical need is to develop methods to effectively empty pits containing both low viscosity liquid waste and dense solid waste. It is not unusual to encounter pits containing dense waste at the bottom with one or more layers of liquid and then solid material above. While the extraction auger can penetrate the solid material, it often forms a ‘posthole’ in the solid material, removing only a small portion of the solid waste. Better methods are needed to mix the solid and liquid material prior to removal. This will improve the performance of the extraction auger, vacuum methods and other extraction technologies.

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## REFERENCES

- Dixon Jr, M. P. & Humphries, E. G. 1995 Evaluation of an Archimedean screw pickle pump/conveyor. *Applied Engineering in Agriculture* **11** (5), 631–635.
- Hawkins, P. 1982 *Emptying on-site Excreta Disposal Systems in Developing Countries: An Evaluation of the Problems*. WHO IRCWD, Dübendorf, Switzerland.
- Ideas at Work 2010 The Gulper – a manual latrine/drain pit pump. [http://www.ideas-at-work.org/pdf/Gulper\\_pit\\_emptying\\_device.pdf](http://www.ideas-at-work.org/pdf/Gulper_pit_emptying_device.pdf) (accessed 15 June 2013).
- Jere, M., Dzatizei, A. T. & Munjoma, M. 1996 Pit-latrines-emptying using motorized equipment. In *Sustainability of Water and Sanitation Systems: Proceedings of the 21st WEDC Conference* (J. Pickford, ed.). 4–8 September 1995, Kampala, Uganda. Loughborough, UK.
- Mara, D. D. 1984 *The Design of Ventilated Improved Pit Latrines*. The International Bank for Reconstruction and Development/World Bank, Washington, DC.
- Muller, M. S. & Rijnsburger, J. 1994 **MAPET: An appropriate latrine-emptying technology**. *Waterlines* **13** (1), 24–27.
- O’Riordan, M. 2009 *Investigation into Methods of Pit Latrine Emptying*. Partners in Development, Pietermaritzburg, South Africa.

- Pickford, J. 1995 *Low-cost Sanitation: A Survey of Practical Experience*. Intermediate Technology, London.
- Radford, J. 2011 *Fluidization of Synthetic Pit Latrine Sludge*. University of Cambridge, Cambridge, UK.
- Roberts, A. W. 1964 [An investigation of grain vortex motion in relation to the performance within vertical grain augers](#). *Proceedings of the Institution of Mechanical Engineers* **178**, 293–310.
- Roberts, A. W. 1999 [The influence of granular vortex motion on the volumetric performance of enclosed screw conveyors](#). *Powder Technology* **104**, 56–67.
- Roberts, A. W. 2001 Design Considerations and Performance Evaluation of Screw Conveyors. *Report prepared for Beltcon 11, International Materials Handling Conference*. Retrieved from <http://www.beltcon.org.za/docs/b1114.pdf> (accessed 24 September 2013).
- Rogers, T. A. 2013 *Modification of Power Earth Augers for Pit Latrine Extraction in Developing Countries*. Master of Science in Environmental Engineering, North Carolina State University, Raleigh, NC.
- Seal, D. 2012 *Identifying Appropriate Pit-Emptying Technologies in a Nairobi Slum Based on Sludge Characteristics and Access*. Cranfield University, UK.
- Still, D. A. 2002 After the Pit Latrine is Full ... What Then? Effective Options for Pit Latrine Management. *Report prepared for the Biennial Conference of the Water Institute of Southern Africa*.
- Still, D. & Foxon, K. 2012 Tackling the Challenges of Full Pit Latrines, Volume 1: Understanding sludge Accumulation in VIPs and Strategies for Emptying Full Pits. Report to the Water Research Commission.
- Still, D. & O'Riordan, M. 2012 Tackling the Challenges of Full Pit Latrines, Volume 3: The development of pit emptying technologies. Report to the Water Research Commission.
- Thye, Y. P., Templeton, M. R. & Ali, M. 2011 [A critical review of technologies for pit latrine emptying in developing countries](#). *Critical Reviews in Environmental Science and Technology* **41** (20), 1793–1819.
- Tucker, J. 2010 Design, Build and Test of a Semi Mechanised Pit Latrine Emptying System for the Developing World, Master of Engineering in Mechanical Engineering, University of Bristol, Bristol, UK.
- Wegelin-Schuringa, M. & Coffey, M. 2000 A small pit emptying machine: an appropriate solution for a Nairobi slum. *Schriftenr Ver Wasser Boden Lufthyg* **105**, 347–352.

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