Adventures in search of the ideal portable pit-emptying machine

DAVID STILL, MARK O'RIORDAN, ANGUS MCBRIDE and BARBARA LOUTON

In South Africa, as in a number of other countries, on-site sanitation has a dominant place in the landscape of basic sanitation infrastructure. If the question 'What happens when the pit is full?' has been thought of at all, it is generally assumed that the pits will be emptied by vacuum tanker. However, owing to site access constraints and the nature of the sludge itself (it can be dense and have a high trash content) vacuum tankers are not always practical. The alternative – manual pit emptying – is hazardous and unpleasant. The Water Research Commission of South Africa funded experimental development of a number of technologies designed to fill the gap between large vacuum tankers and manual emptying. This paper describes these attempts, which include the Gobbler, which uses chains and scoops to lift sludge from the pit, the motorized pit screw auger, which uses a soil auger to lift sludge from a pit, and the NanoVac and eVac, which are small vacuum pumps designed to suck relatively wet sludge from pits. The eVac shows the most promise, but it seems unlikely that any one machine will be able to successfully deal with the greatly varying conditions found in pit latrines.

Keywords: pit latrine, sludge removal, vacuum tanker

SINCE 2000 SOUTH AFRICA has been engaged in a large-scale, supply-driven sanitation delivery programme, with 1.9 million VIPs (ventilated improved pit latrines) and other on-site sanitation systems (Department of Water Affairs, 2013). With a backlog of 2.3 million households still lacking basic sanitation (Department of Water Affairs, 2013) many municipalities are still focused on meeting this need and have not yet turned their attention to the question of what they will do when the systems they have already built reach capacity (Still and Foxon, 2012a). This is expected to happen in the next few years, resulting in an overwhelming demand for pits to be emptied (Still and Foxon, 2012b). Without budgets, policies, tools or procedures in place to manage the emptying of pits and disposal of sludge when this happens, many local authorities may soon be facing a crisis.

A survey of municipalities across the country indicates that there is a general assumption on the part of sanitation managers that they will be able to service VIP pits with a vacuum tanker just as they do septic tanks in the more formal towns. Vacuum tankers are an effective choice of technology where pits are accessible and where waste is fairly liquid and not mixed with domestic solid waste. However, the dry consistency of VIP sludge and the high rubbish content that is found in many

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pits can present obstacles to vacuum removal. In addition, there are households in some of the denser urban settlements with access only by footpaths which cannot be accessed by a vacuum tanker. On narrow roads tankers may encounter other obstacles, such as poor surfaces, low overhead cables, or insufficient space to turn around, which may further limit access. The pits themselves may have been designed without consideration for emptying, and gaining access to the pit may be laborious, involving for example breaking into the latrine via the cover slab or the pit lining.

While a number of smaller tankers (e.g. the Vacutug, the Dung Beetle, the Micravac) have been developed and put into use in different parts of the world, even these more compact vacuum tankers can only be used where access is fair to good (e.g. not soft, muddy, or steep terrain). The Vacutug, developed by UN-Habitat, has undergone testing in a number of countries. In South Africa, it was tested by Partners in Development on pits of low flush systems. While the Vacutug can empty 500 litres of sludge in as little as five minutes if no blockages occur, it travels at a maximum speed of 5 km/h. The distance to the disposal site therefore dramatically impacts how many loads it can empty per day. Weighing over a tonne empty, the Vacutug is also unstable and difficult to move over uneven ground, and can only be moved on steep terrain with considerable effort.

In South Africa the eThekwini Metropolitan Municipality, which has the largest pit-emptying programme in South Africa, has found manual pit emptying with long-handled tools to be the only effective method to service its 35,000 pit latrines. However, manual emptying is difficult, time consuming and, if adequate protective equipment and safety practices are not used, can endanger the health of workers. This work set out to investigate what options there might be to develop a small machine to aid a pit emptier's task.

Designing or selecting an appropriate pit-emptying method

Access to pits varies considerably from town to town and village to village, but if a significant number of pits cannot be accessed except on foot, then the pit-emptying tools must be portable.

A number of further factors specific to the site and the sanitation system must be considered when designing or selecting appropriate methods and equipment for pit emptying. The method must not only be able to overcome obstacles to accessing the site, but also be suited to the design of the pit and the characteristics of the sludge in the pit. The consistency of the sludge will be determined by the amount of water that has been added to the pit through flushing, disposal of grey water, or anal cleansing water as well as the ability of water to leave or enter the pit – which in turn is determined by the pit design, the permeability of soil, and the level of the water table relative to the pit. The diet of pit users, the type of anal cleansing material which they use, and the use of the pit for disposal of rubbish will also affect the consistency of the sludge.

The density of sludge increases with decomposition and settlement over time: water at the top of the pit may have a specific gravity of 1.0 while denser sludge at the bottom of the pit may have a higher specific gravity of 1.5 to 2.0. As a result, it is often easy to extract the low density waste from the top of the pit, while the high density sludge which progressively builds up at the bottom becomes increasingly difficult to remove. While sludge that is less than a year old is generally easy to remove by suction, sludge that is more than two years old can be too dry and dense for removal by suction (Coffey, 2011). Attempts to fluidize older sludge by adding water to the top have been unsuccessful as the water simply remains at the top.

In addition, the interface of the emptying method with transport/disposal methods must be considered. The relative risks to which workers are exposed using this method compared with another must be evaluated, as well as the risk of contaminating the ground, taps, walls or other parts of the household environment with pathogenic material during emptying. Labour and equipment costs, affordability for small entrepreneurs, and the durability and availability of parts must be considered.

Design concepts for portable pit-emptying devices

Three design concepts were investigated in the course of this research: a chain and scoop option; an auger option; and a vacuum pumping option (Still and O'Riordan, 2012).

Chain and scoop: the Gobbler

In 2007 Steven Sugden (the originator of the Gulper) made a manually operated chain and scoop sludge removal device which he called the Nibbler. Only taken as far as prototype stage, the Nibbler was made largely from parts which any bicycle mechanic would be able to maintain. This inspired the development of a somewhat scaled up device which was called the Gobbler (see Figure 1).

Scoops were attached to a heavy-duty chain fitted at intervals with special purpose chain links which are manufactured with angle brackets attached. Initially, two chains were used, guided on their curved path by steel channel sections either side of the scoops. It was found that sludge quickly jammed open spaces, causing the chain to ride off the sprockets. The steel channel was then replaced with large 38 toothed sprockets keyed onto shafts to keep them in place on the top and bottom shafts. These guided the chain around the inside of the bend, moving the shaft out of the path of the scoops. However, sludge again jammed the sprocket teeth and prevented the rolling elements of the chain from seating properly on the sprocket. A sprung scraper was then added to remove waste from the scoops (Figure 2) which allowed the entire design to be simplified significantly: the bend in the chain was eliminated, only a single chain was used and the cog at the bottom of the mechanism was replaced with a simple guide wheel.

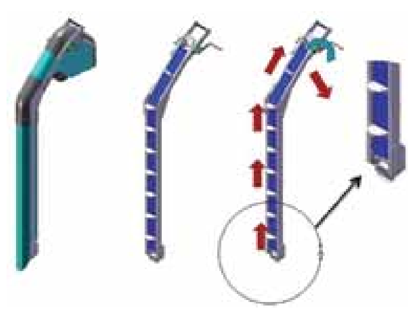

Figure 1 The Gobbler chain and scoop pit-emptying concept

Figure 2 The sprocket drive and sprung scraper at the top of the Gobbler

While the concept of the Gobbler was simple enough in principle, and it was tested with modest success on pig slurry, field tests demonstrated that the machine was just too unwieldy and too prone to jamming to be a likely solution to the pit-emptying problem.

Pit screw auger

Anyone who has seen an Archimedes screw pump in operation might have wondered if a similar principle could not be used to lift sludge out of a pit latrine. In fact the Archimedes pump is suitable for fluids, and what is needed is an auger, which also uses a positive displacement principle. Augers are found in the civil engineering and agricultural sector where they are used for making holes in the ground or for lifting a product such as grain from one level to another.

Initially, a manually powered auger was designed with the aim of producing a device that could be operated by a single person and remove dry waste from a pit through a pedestal and into a container. Manual operation proved impractical, however, as the cranking speeds required to lift the sludge were too high. With the addition of a motor it was found that at speeds from 60 RPM to 120 RPM the rate of removal remained static at approximately 25 litres per minute. The limiting factor was found to be the auger point itself – in particular the length of the auger protruding from the sleeve, the diameter, and the pitch.

Different diameters and internal finishes were tested for the pipe shrouding the auger. The use of a helically lined pipe (flexible hose) did not improve lifting but rather increased friction in the pipe. A 125 mm outside diameter uPVC pipe, with no helix, proved the most successful. A 15 mm gap between the auger flight and pipe was found to be optimum.

While the auger proved able to handle some of the rubbish present in the pits, larger objects and rags did occasionally jam the mechanism. The ability to reverse the direction of the auger is helpful for unblocking the auger, but sometimes unblocking requires removal of the shroud. A cage was tested at the bottom of the pipe to prevent larger objects from being taken up into the auger, but this prevented dense sludge from moving towards the auger point. Instead of a cage, three blades were then added to the bottom of the screw to increase the auger's ability to cut through waste and draw dense waste into the screw.

Discharging the sludge from the top of the auger proved challenging. A larger diameter pipe fitted at a 45-degree angle was tested for discharge, as were a long radius elbow termination, a short elbow, and a 45-degree plate. The auger could achieve a 400 mm delivery head before the motor cut out, but the waste became progressively more compacted as it rose above the auger, tending to rise past the side opening rather than falling out and then jamming beneath the motor. Finally, a section of reverse screw auger mounted inside a 45-degree T-piece proved successful (see Figure 3).

It was important that the auger did not continue past the outlet as this resulted in the sludge being compacted between the top of the auger and the bottom of the motor. Testing demonstrated that a continuous length of auger, rather than sections with a gap between, is needed and that the outlet must be at or just above (within 50 mm) the top of the auger for waste to be easily forced out.

A 1 m length of 110 mm flexible pipe was fitted to the sludge outlet after testing layflat hose and heliflex. This enabled sludge to be directed into the collection vessel while significantly reducing operator contact with the sludge. A hook was added from which to suspend the bucket during emptying.

An extension to the auger was tested. To add the extension piece, the shrouding had to be removed, the extension screwed on, the shrouding remounted and a shrouding extension mounted. Since the mechanism measured over 2 m in length with the extension, under conditions where a pit was emptied directly through the pedestal it would have to be coupled with part of the auger in the pit. While the extension almost doubled the length of the auger, the relative lifting distance was still not great.

A series of tests was conducted using simulated pit latrine sludge made with pig slurry. The auger was able to fill a 25 litre bucket in 38 seconds, which equates to a rate of 40 litres/minute. The consistency of the slurry was varied by the addition of quantities of newspaper, rags, and plastic bags to more closely approximate the waste found in pit latrines. The auger performed well during all tests and there was no significant reduction in the time taken to empty the pit when the rags and plastic were added.

One of the main disadvantages of the auger was its weight and size. The empty weight was 20 kg and in operation the auger plus sludge can weigh in excess of

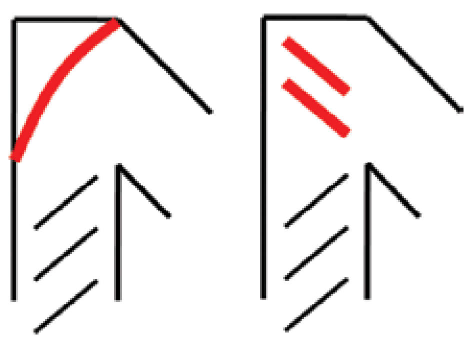

Figure 3 The sludge raised by the auger did not exit down the side chute when a simple curved guide plate was used. However, the addition of a short section of auger with the flights oriented in reverse did solve the problem of how to get the sludge to fall out of the auger

40 kg, which is too heavy to manoeuvre easily inside the pit. A number of ideas were tested for providing support to the auger: hanging it from a bungee cord; mounting it on a ball joint which could be lifted up and down on a jack; and hanging it from a chain block supported by a tripod. Of these the latter was the most practical, but it did mean that if the pit could only be accessed via the inside of the superstructure, the roof would have to be removed (see Figure 4).

The first field test on an actual pit latrine (see Figure 5) was a complete failure. It was concluded at the time that the nature of the trash found in pits in the field was different from that used in the simulations, and that this trash was jamming the auger and rendering it useless. However, this conclusion may perhaps have been premature as it was later discovered that the pit on which the auger had been tested comprised a top layer of solids and scum perhaps 400 mm thick, below which the pit contents were very liquid. The auger point had been inserted into this liquid portion in which it was ineffective.

At this point further development work on the auger was halted in order to concentrate on a small vacuum pumping machine. It must be mentioned, however, that a team based at North Carolina State University in the USA under the leadership of Professors Borden and de los Reyes is taking this concept further. Their auger uses hydraulics to drive the auger, which improves the power to weight ratio and allows the operator to vary the rotational speed. The NCSU team carried out field tests with PID in South Africa in March 2013, and these demonstrated that the auger could empty VIP sludge given the right conditions. The team identified various avenues for the improvement of the technology and hopes to continue development work.

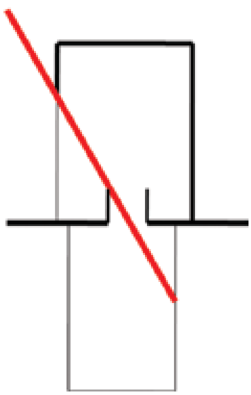

Figure 4 The auger has to be at least 2 m long in order to empty even just the top metre from a pit latrine. This means that access to the pit from the outside of the structure is needed for the auger to be practical (see Figure 5)

Figure 5 The first field test of the pit sludge auger on a pit latrine

The NanoVac

The MAPET (Manual Pit-latrine Emptying Technology) was developed and piloted by the Dutch NGO WASTE in Dar es Salaam in the early 1990s. A vacuum was produced in a 200 litre steel tank using a manually operated piston pump (Muller and Rijnsburger, 1992). The equipment was portable and worked well on the liquid sludge typical in Dar es Salaam. The MAPET was never adopted at scale, however.

The NanoVac (see Figure 6) was based on the concept of the manually operated MAPET but driven by a 5.5 hp internal combustion engine. As the pump and the vacuum tank were kept separate, they were still small enough to be carried by two or three people to the emptying site.

The NanoVac was designed, like the MAPET, with two large diameter piston pumps to suck and blow air, rotating 180 degrees out of phase to reduce cyclic loading on parts. The pistons' seals were made from leather cut from a welder's apron so that they could be easily replaced.

Initially, a 1 kW electric engine was used with an 80 mm/800 mm pulley system for speed reduction. With very short stroke lengths, high RPMs were not effective as the air was just 'excited' inside the piston and did not actually act to create a

Figure 6 The NanoVac uses two PVC piston pumps driven by a combustion engine to produce a vacuum in a vacuum tank (not shown here)
Note: The tank and the pump are small enough to be carried by two or three people to any location accessible by foot. The machine works but would need to be made of more robust materials to last long in the field

vacuum, while with very long strokes the motor struggled to turn the cranks at high speeds due to the larger turning moments of the pistons. A compromise between a longer stroke length and faster RPM proved optimal. The final design used a 5.5 hp combustion engine coupled to a 1:20 reduction box along with a 1.5 reduction pulley drive, driving two 100 mm diameter pistons with 150 mm stroke lengths at 200 RPM.

The concept of using a piston as a vacuum pump for sucking waste that is relatively liquid proved effective with several different arrangements. However, despite proving successful in trials with pig slurry, the NanoVac was not robust enough in field tests. A stronger frame and better wearing materials for the pistons would be required for further development.

The eVac

Development of a portable vacuum pumping machine then moved on to the eVac (Figure 7), which was built around an off-the-shelf oil-lubricated vane pump which produced an air flow of 300 litres/min at 0.5 bar vacuum. The pump was driven by

Figure 7 (left) The eVac assembly with electric motor (bottom right) and moisture trap (top left). The vane pump is obscured by the moisture trap
Figure 8 (right) The self-sealing cover of the vacuum tank with float cut-off valve (below), air suction line and vacuum release valve (top left), and sludge suction line (top right)

a 1.5 kW (2 hp) single phase electric motor, which could be powered by a portable generator if power was not available on-site. The pump and motor were connected by a belt drive and mounted on a custom fabricated steel trolley. While the trolley unit weighed a total of 63 kg it proved stable and easily manoeuvrable across rough ground and could be lifted onto a vehicle by two people.

Two float valves and a moisture trap protected the pump from the entry of sludge. The primary float valve was made using a squash ball in a short length of PVC pipe over the vacuum outlet and attached to the lid of the sludge collection container (see Figure 8). As sludge filled the tank it lifted the ball until the ball sealed off the vacuum line, preventing sludge from continuing to be sucked into the tank and on through to the vane pump mounted on the trolley. However, this arrangement could not prevent some sludge from getting into the air vacuum line through splash action. A moisture trap was therefore mounted on the trolley just before the pump. This was made using a 320 mm length of clear 140 mm diameter PVC pipe with two end caps. Sludge escaping past the primary float valve entered this container through a hole in the lid, and gravity prevented sludge from exiting through the suction line. In the event that the trap filled with liquid a second float valve would block the suction line. However, a brass one-way valve at the bottom of the trap allowed the contents of the trap to drain under gravity every time vacuum pressure was released. While this protected the pump, it introduced the risk of contaminating the ground beneath the moisture trap. A separate container is therefore needed to collect any sludge draining from the moisture trap.

A trolley-mounted fibreglass vacuum vessel for the collection of the sludge was initially made with a capacity of 100 litres. When the volume of the tank was increased to 180 litres, its size made it awkward to move. At this point it was realized that the use of a number of small interchangeable vacuum vessels was more appropriate than one larger vacuum vessel. Apart from the greater portability of smaller containers, a small pump can produce a working vacuum relatively quickly in a small container, but only slowly in a larger container. It is therefore important that the vacuum tanks are sized to match the equipment being used. Roto-moulded containers with a 47 litre capacity were made using linear low-density polyethylene (LLDPE). These were 770 mm high with a 310 m diameter (reasonably convenient dimensions, but they were used because the local rotomoulders happened to have a mould of that size available). A wall thickness of 7 mm in the initial design proved inadequate to withstand the vacuum without implosion. The design was revised to use 14 mm walls. Each container weighed 9.6 kg when empty. These vessels allowed the waste to be extracted by the 'plug and gulp' method, where the hose is thrust in and out of the sludge, using a combination of suction and air flow to move the sludge up the pipe.

Two types of lid were designed to enable two alternatives for emptying the vessel: the 'suck only' arrangement, in which sludge was sucked into the vessel and then tipped out of the vessel into a disposal pit or drum; and the 'suck and blow' arrangement, where sludge was sucked into the vessel and then expelled through a second hose.

Figure 9 The eVac in operation with interchangeable vacuum vessels

For the 'suck only' arrangement, an interchangeable lid, with the air and sludge lines attached, was used with multiple vessels. Once one vessel was filled, the lid was moved to an empty vessel and the full vessel was emptied by tipping it into a disposal pit or drum. The lid was made of 8 mm steel plate with a thinner steel shim around the edge to enable it to sit evenly on the vessel. The lid was held on to the container by the force of the vacuum alone. A foam rubber strip on the underside of the lid enabled an airtight seal to be formed. The airline was connected to a 1 inch (25 mm) T-piece attached to the lid. A 3 inch (76 mm) steel elbow connected the sludge hose to the container (Figures 8 and 9).

When working with the eVac in the 'suck and blow' configuration, only one container was used. Rather than have an interchangeable lid which was moved between containers, the lid was bolted onto the container, only to be removed for maintenance or in exceptional circumstances. This allowed the container to withstand positive pressure as well as a vacuum. The container required two air hoses: one for vacuum and one for pressure. These hoses both passed through three-way valves before entering the container. On each of the valves one side was open to atmospheric pressure and the other to a steel 'T' which joined the container. The sludge inlet pipe was connected to the lid, while the sludge outlet layflat hose was connected through an attachment at the bottom of the container. The total weight of the container was 27 kg, allowing it to be carried by one person when empty. As it did not need to be moved once in position its weight did not pose a problem.

To carry air, 1 inch (25 mm) diameter flexible hoses approximately 3 m long were used. A 5 m, 3 inch (76 mm) flexible 'heliflex' hose was used for the sludge suction. The hose was connected to the container lid using a 3 inch (76 mm) camlock coupling, which provided a good seal but could be difficult to operate if it was soiled. A plastic bushing reduced the diameter of the entry point of the sludge suction hose in order to prevent objects large enough to cause a blockage from entering the hose. A stainless steel pole was strapped to the hose to aid with manoeuvring it around the pit.

Working with the 'suck only' tank, no difficulties were encountered emptying pits with relatively wet contents and the 40 litre containers filled in less than 10 seconds. The critical factor in determining the speed of the emptying cycle was the time it took to walk with the containers to the disposal pit or drum and back. Significant splashing and spilling occurred, contaminating the area around the pit. It proved more difficult to remove dry sludge in a VIP pit with the eVac. An air/water lance (using the exhaust pressure from the vane pump routed through a pressure vessel partially filled with water) was used to fluidize the sludge enough for the eVac to lift it but progress was still slow.

The filling rate proved even faster with the 'suck and blow' tank when working with relatively wet sludge. This could be attributed to the volume of sludge at the bottom of the tank which was not emptied out at the end of the cycle and the sludge inlet pipe remaining largely full between cycles. Blowing the waste into the disposal pit also proved efficient, as did switching the valves between suck and blow. The total time to empty including setting up, emptying, and packing away was approximately 45 minutes.

The current cost of producing an eVac is estimated at US$2,400, excluding the generator.

Conclusions

This research and development work focused on three pit-emptying technologies. The Gobbler, based on a chain and scoop concept, proved to be heavy and awkward to manoeuvre and jammed easily in sludge. The pit sludge auger was able to lift a thick pig slurry at a rate of 25 litres per minute but was not successful when tested on actual pit latrines, possibly because of the trash content, but more likely because it was inadvertently placed in a watery layer below a solid scum layer. The auger was also heavy and awkward, and proved inefficient if the sludge was too dry to flow towards the auger intake. The eVac (successor to the NanoVac) was the most successful of the PET technologies developed under this project. It was able to evacuate the sludge from low flush or pour flush latrines without difficulty, and also coped well with the sludge from a number of wetter pit latrines. However, when it was tested on dryer pit latrine sludge it was not very successful. In such cases vacuum pumping requires the continuous addition of water and the mixing of the sludge, and a more powerful vacuum pump.

Pit emptying requires a range of tools and the eVac would be a useful addition to the pit emptier's toolkit. However, it remains to be seen whether the owner of a pit-emptying business would see the value in a machine such as an eVac over the standard tools of buckets, shovels, and fully manual pumps such as the Gulper. As Steven Sugden has emphasized in several forums, the emptying of the pit is a relatively small part of the total faecal sludge management operation (empty – transport – dispose), and therefore it does not automatically follow that a machine that speeds up pit emptying per se will be seen as an attractive investment (Sugden, 2012). The eVac does offer a means by which pit emptying can be made somewhat less messy and unpleasant work, which should be worth something. The only way to find out whether it is worth enough is to test the market.

So what if the pit is full?

While focusing on pit emptying, sight should not be lost of other arguably more sustainable and/or more intelligent solutions to the problem of full pits, which include the following:

- Use of urine diversion toilets with small vaults that are easily accessed and manually emptied.
- Use of pour flush toilets with offset alternating pits of a manageable size which are easily accessed and manually emptied (Still and Louton, 2012).
- Use of large pits (3.5–4.5 m^3) which if not also used as rubbish disposal pits can last for 20 years and more, and which are abandoned when full.
- Use of prefabricated lightweight toilets which are designed to be moved when the pit is full.

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