Variant Design and Fabrication of an Earth Tunneling Machine

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***Abstract*—Earth tunneling machine is an equipment used in drilling tunnels under the road surface for the laying of pipes or cables. The earth tunneling machine was produced locally using available materials through simple machining and joining processes. The machine comprised major components like the driving shaft/boring head, the pulling mechanism, the sand extraction system, the control unit, the machine base and housing which were locally produced and assembled. Using the machine to drill soil samples from Ekpene Ukim- Uruan; Mbiabong – Uyo; Ikot Obiodongo – Ibesikpo; and Anua Obio - Uyo, the strength of soil samples by the California Bearing Ratio (CBR) test at drilling depths was determined to be 0.444 MPa, 0.417 MPa, 0.420 MPa, and 0.458 MPa, respectively. The test result demonstrates the performance of a functional model earth tunneling machine, thus indicating the realization of the objective of the research work**

***Index Terms*—Components; Design; Drill; Fabrication; Soil; Tunnel.**

I. Introduction

Most often, in a bid to lay underground cables and pipes to enhance wider telecommunication coverage in some urban areas, a good portion of an already constructed road is often damaged, resulting in an uneven road surface that affects road users, especially motorists. This work attempts to design and fabricate a prototype earth tunneling machine, using locally sourced materials. Currently, the available variants in the market operate on the principle of a rotating toothed-cutter mounted at the end of the machine housing, drilling while various apparatuses like augers and back hoe type are used to remove the loosened soil. Some current earth tunneling machines are fluid-driven while others make use of internal combustion engines.

Tunneling entered a period of major development in the 19th century in response to the demands of industrial development. Population movement and a shift to industry led to the construction of road, rail and canal tunnels, and also the need to install main sewer systems in cities. This in turn created a demand for tunnels locations that required a new approach [1].

The most famous example is the tunnel under the Thames designed by Marc Brunel and constructed by his son Isambard Kingdom Brunel. Similar to most tunneling jobs, it encountered problems because it was situated not far below the bed of the river in very soft, saturated soils. The work started in 1825 but was not opened to the public until 1843. Two things are significant about this tunnel; Mr. Brunel introduced the concept of the tunneling shield, and the tunnel is still in use today as part of the London underground [2].

These early 19th century tunnels were built lined with brick which was laborious, slow and hazardous work. British engineers P.W. Barlow and J.H. Greathead obtained a patent on a circular shield in 1864. Mr. Greathead used it in 1869 to drive a pedestrian tunnel under the Thames without undue problems. The Barlow-Greathead shield had three major advantages – simplicity, safety and speed, introducing three major innovations that are still in use today:

- Cast iron segments to line the tunnel;
- Compressed air to keep the water at bay; and
- A grouting pan to inject grout into the voids behind the segments [3].

However, the limitation, which existed, was that the minimum diameter that could be economically driven for a traditional tunnel was around 2,000 mm. This is created by the need to erect the lining using labour behind the advancing shield [4].

The concept of a slurry pressure balance shield was put forward in patents in the UK and Germany in the late 19th century. In the mid-20th century, various designs were patented including one in Germany using bentonite slurry. The first machine with a cutting wheel and hydraulic mucking was used in Japan in 1967 [5]. Another development of this kind saw an introduction of a rear compartment containing air under pressure that acted on the slurry. In 1972, a prototype was built and used to drive a tunnel under the port at Hamburg. Modern versions of this concept have been widely used [6].

In parallel, but quite independently, another development was underway. This was the concept of jacking in from the drive pit pipe sections behind the cutting shield to line the tunnel. By no means was this a new concept. Records of early simple pipe jacking go back to the late 19th century in Vienna and the USA. The primary use was to install relatively short lengths of casings under rail tracks and roads. Men worked at the face excavating the soil. It would appear that many of the pipes were fitted with a leading steel cutting edge [5].

Pipe jacking offered a solution that allowed short crossings up to 150 m to be made in a way that was inherently safe as well as economical. The ability to tunnel smaller than traditional diameters was one advantage. Operatives could be trained more quickly in the skills for pipe jacking than in the skills required to drive a timbered heading [5]. Installing sewer pipes required pipe jacking to be undertaken at greater depths and in less cohesive ground conditions and over longer lengths. It prompted a demand for controllable mechanized excavation and spoil disposal.

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In Japan there was a large market for sewers less than 2,000 mm to be installed without disruption. The limitations of segment tunneling prompted the development in Japan of remotely controlled miniaturized pressure balance shields [4]. The bringing together of remote control shields and the principle of pipe jacking created the major change in the installation of small to medium diameter tunnels and sewers. Pipe jacking was limited to man-entry sizes and cohesive or pre-treated unstable soil. Japanese manufacturers combined the two methods and used the principle of pipe jacking concrete sewer pipes in diameters greater than 1,500 mm with remote control shields that could counterbalance groundwater and soil inflow. As the demand shifted towards installing smaller diameter pipes, the Japanese developed miniaturized versions of the larger machines [4]. These became known as micro-tunneling machines. An operator at a control panel could remotely install pipes as small as 300 mm, with workers only needed in the drive pit to add the pipe sections. [7].

The California Bearing Ratio (CBR) Test is a relatively simple test that is commonly used to obtain an indication of the strength of a subgrade and base material including recycled materials for use in road and airfield pavement. It may be thought, therefore, as an indication of the strength of the soil relative to that of crushed rock. The result obtained from the CBR test will help the designer and engineer to determine the thickness of the various layers (sub-base, base materials, binder and wearing course) of a flexible pavement. [8].

II. Materials and Methods

The selection of materials for the production of the earth tunneling machine was dependent on the design considerations, taking into account the stresses to which the machine will be subjected and the functional requirements.

A. Materials

The materials for the fabrication of an earth tunneling machine include mild steel sheets, shaft and angle bars of varying thicknesses (1mm, 3mm, 5mm, and 20mm), drilling and pulling motors, driving and driven pulleys, 1hp electric motor, A-24V belt, M12 bolts and nuts, 12V battery, control switches and M18 lead screws. The earth tunneling machine consists of the following functional systems – the driving shaft/boring head, the machine housing, the pulling mechanism, the sand extraction system, the control unit and the machine base.

B. Methods

The different components of the earth tunneling machine were designed, dimensioned, cut out and machined to designed specifications accordingly. Certain parts were joined together by arc welding while others were screwed. The head of the shaft was permanently welded to an M8 bolt using arc welding, such that the cutting head can be screwed as an attachment to it. The end of it was attached to the pulling motor for direct transfer of motion. At the end part of the shaft, another shaft of 5mm was machined using the lathe, joined permanently by arc welding in such a way that its movement is relative to the drilling motor. The pipe to be laid was selected at 50mm. Using an M13 nut, it was firmly clamped to the pipe holder, making it possible for it to be pushed forward with the machine housing as the drilling progresses. The machine housing is where the driving force/torque is generated. It has a 1HP electric motor as its prime mover. The boring motor rotates at a speed of 40 rpm. Under the boring motor, there is a boring motor mount permanently welded. The support carries an M18 bolt which was welded permanently to it. The nut which is threaded at equal pitch with the lead screw guides the machine housing to slide forward and backward, relative to the direction of the feed motor. The boring motor was fastened to the metal base with M13 bolts and nuts. The pulling mechanism has as its prime mover a feed motor which is enclosed in the base of the machine. A lead screw with threaded pitch was connected to this electric motor via a pulley belt arrangement, such that its movement is relative to the feed motor. Inside the machine housing, there is a boring motor support connected to the lead screw (with the same pitch as the lead screw). As the feed motor moves clockwise, the machine housing slides forward (along the rails, towards the tunneling direction) and as it moves anti-clockwise, the housing slides backward. For precision, while carrying out tFhe tunneling operation, a guide was attached to the end of the machine base. The Archimedes’ screw was fabricated on the mild steel solid shaft; the shaft was cut with hack saw and its head arc-welded to an 8mm threaded bolt, forming a pivot head. Thereafter, the path for the Archimedes’ screw which was marked out on the shaft using the scriber before a ¼ rod, was welded to follow the marked path. This was later grinded to shape using the grinding machine. The base is the box-like enclosure that carries the feed motor and the pulling mechanism. Its structure is made of 5mm thick angle bar which was first marked out and cut to specified lengths before assembly to shape as shown on the working drawing. The control system is a hand-held switch that has buttons on it for the boring motor and the feed motor controls. It adopts a simple connection of two relays and a 12V battery to power it. The assembled earth tunneling machine is as presented in Fig. 1.

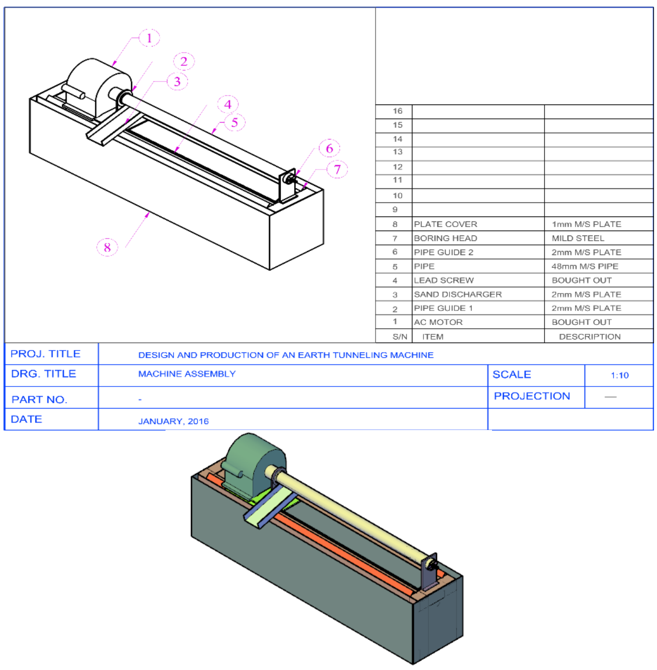

Fig. 1. Assembled earth tunneling machine

C. Determination of Key Design Parameters

The torque on the cutter was determined as follows;

Angle of Inclination of the cutter w.r.t the axis of the cutting head, '∝' = 45°. Width of the cutter blade, 'b' = 15mm. Area of the face of the cutter, 'A':

$$A = L \times b = 26 \times 15 = 390mm^2 \quad (1)$$

So, pressure applied by the soil during rotation of the cutter is subjected on the area 'A.sin(α)' and the load during linear translation lies on 'A.cos (∝)'. Bearing strength of soil, 'σ' = 0.442MPa.

$$F = \sigma A \sin(\alpha) = 0.442 \times 390 \text{ Sin } (45) = 121.89 \text{ N} \quad (2)$$

to obtain the torque:

$$\text{Torque} = F \times L = 121.89 \times 26 = 3.17\text{Nm} \quad (3)$$

1) Forces Acting During Linear Translation

Bearing strength, σ = 0.442MPa
Angle of Inclination of the cutter, '∝' = 45°
Width of the cutter blade, 'b' = 15mm
Length of blade, 'l' = 52mm
Width of blade = 15mm
Number of blades, 'n' = 2
So, Area under subjected load:

$$A\cos(\alpha) = bl\cos(\alpha) = 15x45x\cos 45 = 551.54\text{mm}^2 = 5.52x10^{-4}m^2 \quad (4)$$

So, force acting during linear translation:

$$F = A\cos(\propto)\sigma = (5.52x10^{-4})x(0.442\,x10^{-6}) = 243.98 \quad (5)$$

2) Power Required from the Boring Motor

Let speed required be 'N' ($r$pm)

$$\omega = \frac{2\pi N}{60} = \frac{2x3.142x120}{60} = 12.57\text{rad/sec} \quad (6)$$

$$\text{Power} = \text{Torque} \times \omega = 243.98 \times 12.57 = 3066.83 = 3.07\text{kW} \quad (7)$$

3) Tension on the Belt of the Feed Motor

Tension on belt on the tight side, 'T_1'
Tension on belt on the tight side, 'T_2'
Angle of contact in radians (ie Angle subtended by the arc AB along which the belt touches the pulley at the centre), ϴ
Velocity of the driving motor, v
Radius of the driving pulley, 'r_1'
Radius of the driven pulley, 'r_2'
Distance between pulleys, 'x'
Coefficient of friction between the belt and pulley, μ
Angle between the pulley axis and the point of contact on the pulley, α:

$$\sin\alpha = \frac{r_1 + r_2}{x} = \frac{0.01+0.08}{0.183} = 0.4918 \quad (8)$$

Angle of contact:

$$\Theta = 180 + 2\alpha = 180 + 2x(29.45) = 238.9^{\circ} = 4.17\,rad \quad (10)$$

4) Tension on the Belt

$$2.3 \log\frac{T_1}{T_2} = \mu\Theta = 0.25\,x\,4.17 = 1.0425 \quad (11)$$

$$\log\frac{T_1}{T_2} = 2.8399,\ T_1 = 1000, \quad T_2 = \frac{T_1}{2.8399} = \frac{1000}{2.8399} = 352.13$$

5) Power Transmitted

$$P = (T_1 + T_2)v = (1000 - 352.13)x1.213 = 0.786 \text{ kW}$$

III. Result and Discussion

The different components were assembled and the result was a tested and functional model earth tunneling machine. It operated properly and had no wobbling effect on its shaft connection. The electric motors ran properly and all connections were well fitted. A multimeter was used to test the supply voltage entering the electric motor and it measured 230V, thus conforming to the result on matching the unit to the correct operating voltage.

The boring motor was switched on and the drilling shaft rotated at the required speed of 120 rpm thereby rotating the drilling head. The feed motor was later switched on and the motion on the shaft of the motor was transferred by the driving pulley to the driven pulley and then to the lead screw perfectly without vibration. The machine was subjected to a tunneling operation and it was observed that it took 7 minutes for a 1m pipe to be laid. After this operation was carried out, it was revealed that the mechanism adopted for the design of the machine was good in its operation. The machine was subjected to multiple tests at four different sites and result obtained. The CBR test result obtained at Ekpene Ukim, Uruan is presented in Table I and the Compression force vs Penetration curve is presented in Fig.2.

TABLE I: THE CBR TEST RESULT OBTAINED AT EKPENE UKIM, URUAN IN JANUARY 2016

SAMPLE REF.	WIS-1			Weight of Sample(g)			6000
SAMPLE LOCATION	EKPENE-UKIM - URUAN			Number of Blows			55
Water Additive (ml)	768			Rammer Weight (kg)			2.5
		UNSOAKED					
Moisture Content Tin No.		penetration (mm)	DIAL READING				
Weight of Tin + Wet Soil (g)			Top	Bottom			
		0.00	0.00	0.00			
Weight of Tin + Dry Soil (g)		0.50	90	50			
Weight of Empty Tin (g)		1.00	150	95			
Weight of Water (g)		1.50	245	195			
Weight of Dry Soil (g)		2.00	330	295			
Moisture Content (%)		2.50	420	370			
Target Moisture Content (%)		3.00	490	440			
Weight of Mould + Soil (g)		3.50	550	500			
Weight of Mould (g)		4.00	620	580			
Weight of Soil in Mould (g)		5.00	690	645	$CBR_{2.5}$ (%)	=	f/13.44kN
Soil Wet Density (g/cm^3)		6.00	750	690	CBR_5 (%)	=	f/20.16kN
Weight of Soil in Mould (g)		7.00 8.00	810 885	750 805	*CBR =*		*33.11 %*
Dry Density of Soil in Mould (g/cm^3)		CBR at 2.5_{Top}	31.25		CBR at 5.0_{Top}		34.23
MDD (g/cm^3)	1.70	CBR at 2.5_{Btm}	27.53		CBR at 5.0_{Btm}		31.99
OMC (%)	12.80	Avg. CBR at 2.5	29.39		Avg. CBR at 5.0		33.11

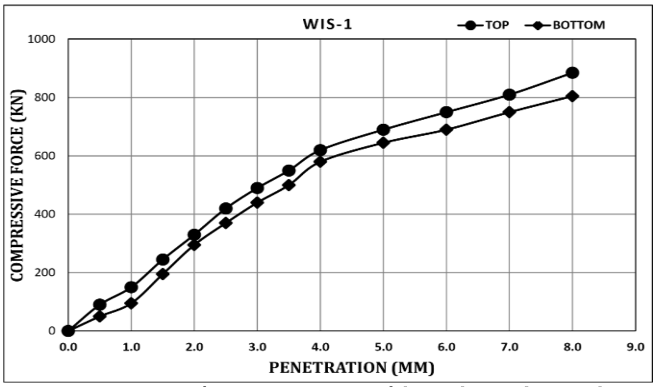

Fig. 2. Compression force vs Penetration of the earth tunneling machine

IV. CONCLUSION AND RECOMMENDATION

– The aim of producing an earth tunneling machine using local available raw materials was achieved. The machine was tested at four different sites and good result was obtained to demonstrate the usefulness of the model machine for instructional purposes.

– Further modifications are recommended to for the machine to carry out directional drilling to avoid digging beside the road surface before carrying out the tunneling operation.

REFERENCES

[1] T. Iseley, *The Technology of Tunneling*, California, Craftsman, 1991.
[2] H. Loretta, (July 2015) A Short History of Tunneling, Available: http://pisces.sbu.ac.uk/BE/CECM/Civ-eng/tunhist.html
[3] S. Bebendererde, “Advanced techniques for EPB-TBM operation,” *Tunnel et ouvrage, outerraim,* 128, 1995.
[4] N. Barton, *TBM tunneling in jointed and faulted rock,* Utrecht, Balkema Press Inc, 2000.
[5] L. O'Connor, *Tunneling Under the Channel*, New York, Suny Press, 1993.
[6] D. Burroughs, *Depressing Traffic Top-Down*. Florida, Roland Publishing Incorporated, 1994.
[7] A Foley, (2009). Life on the Cutting Edge: Dick Robbins, *Tunnels & Tunneling International*, 2009, Available: www.tunnelsonline.info.
[8] R. Liv, and C. Evett, *Geotechnical Properties of Soils*. New York, Suny Press, 2003.