Design of a manual press for the production of compacted stabilized soil blocks

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In this paper, we discuss the design of a manually operated soil compaction machine that is being used to manufacture stabilized soil blocks (SSB). A case study of manufacturing more than three million blocks in a housing project using manually operated machines is illustrated. The paper is focussed on the design, development, and evaluation of a manually operated soil compaction machine for the production of SSB. It also details the machine design philosophy, compaction characteristics of soils, employment generation potential of small-scale stabilized soil block productions systems, and embodied energy. Static compaction of partially saturated soils was performed to generate force-displacement curves in a confined compaction process were generated. Based on the soil compaction data engineering design aspects of a toggle press are illustrated. The results of time and motion study on block production operations using manual machines are discussed. Critical path network diagrams were used for small-scale SSB production systems. Such production systems generate employment at a very low capital cost.

Keywords: Compressed earth block, soil compaction, soil block, toggle press.

Introduction

EARTH materials include minerals, rocks, soil and water. These are the naturally occurring materials found on Earth that are widely used as raw materials to construct buildings and other structures. For example, cob walls, adobe bricks, wattle and daub, rammed earth, are a few pure earth-based wall construction techniques. But the major drawbacks of pure earth-based constructions are loss of strength on saturation and erosion due to rain impact. In order to impart strength to earth-based construction material and to avoid erosion during rains, the soils are first stabilized and then used for construction. To stabilize the soil, inorganic binders such as Portland cement and lime are commonly used. Using a machine, these stabilized soil blocks (SSB) or bricks can then be produced by compaction of processed soil and stabilizer mixture at optimum moisture content. Stabilized soil block technology has several advantages, such as low embodied carbon, decentralized production, recyclability, eco-friendliness and others. The technology of SSB is five to six decades old. Several studies dealing with various aspects of SSB technology such as optimum soil grading, strength-density relationships, characteristics of SSB in dry and saturated state, behaviour of SSB masonry walls, mortars for SSB masonry and others have been undertaken. Information on stabilized soil block technology can found in the several studies[1–9] and many other publications.

Even though there are several studies on various aspects of SSB technology and manual machines for SSB production are available in the market, there are hardly any investigations on the machine design aspects for manual production of SSB in a decentralized manner. Design and development of a manually operated machine for SSB production involves understanding the compaction characteristics of wide variety of soils, analyzing a suitable machine mechanism to match the force-compaction stroke relationships for soils, machine design and analysing the manual production process for maximizing the block production. Therefore, the present study aims to examine the machine design process and monitor the block production system in an actual SSB production centre employing the manually operated machines.

Soil compaction process and machines for SSB

The simplest way to produce soil block (SSB) is by tamping the processed soil in a mould with the help of a tamping rod. However, the degree of compaction cannot be easily controlled in this process and the productivity will be low. Machines are employed for the production of SSBs. These machines can be broadly grouped under two categories: (1) manual machines and (2) mechanized machines. The mechanized machines are ideally suited for industrial production system, whereas the manual machine/press are well suited for decentralized production systems. The mechanized machines generally use hydraulic power pack to generate large amount of compaction force. The manual machines generate adequate compaction force using animate energy. In the manual machines, the processed soil is compacted employing the static compaction process. The static compaction process

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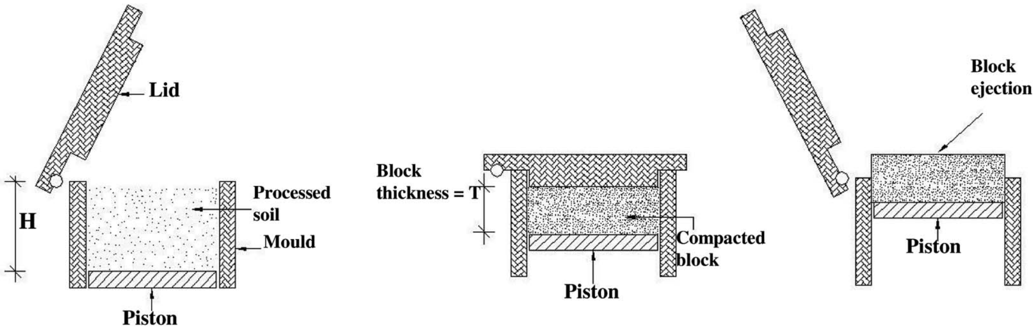

Figure 1. Static compaction process.

involves confined compaction. Wetted mixture of soil, stabilizer and water is compacted into a dense block in a mould using a piston either from one side or from both sides. The energy supplied in the compaction process is not a unique value. It depends upon the soil composition, moisture content and the targeted block density. Three stages of static compaction process employed in the production of SSB using manual machines are shown in Figure 1.

The design of a manual machine/press used for the production of SSB requires the following information. (a) Force–piston displacement (stroke) relationships for compaction of soil mass and the peak force, that is the compaction characteristics of soils. (b) Machine mechanism to match the force–stroke relationship of the soil mass. (c) Block or brick dimension (soil mass) to match the available human energy supply during compaction.

Compaction characteristics of soils

Soil compaction is generally studied with reference to a standard test, such as the ‘Standard Proctor compaction test’. In this type of test, a definite amount of energy is provided to the soil mass while compacting it. Such a test reveals the optimum moisture content and the corresponding maximum dry density for the standard energy input, but it does not yield any information on the force needed in a static compaction operation used in the SSB production. In a static compaction operation, the force needed to achieve a particular density will depend upon the size of soil mass under compaction. A direct test to evaluate the force on a soil mass during compaction is hence desirable. The task of the soil compaction machine is then to produce the desired force variation. Thus, the force–deflection (stroke) relationship of the soil mass is a basic prerequisite in designing the soil compaction machine.

The force–deflection (stroke) relationship of a soil mass will depend upon the following: (a) The final density of the compacted soil mass to be achieved, (b) Moisture content of the soil mixture during compaction. (c) Soil composition (quantity of sand, silt and clay fraction in the soil).

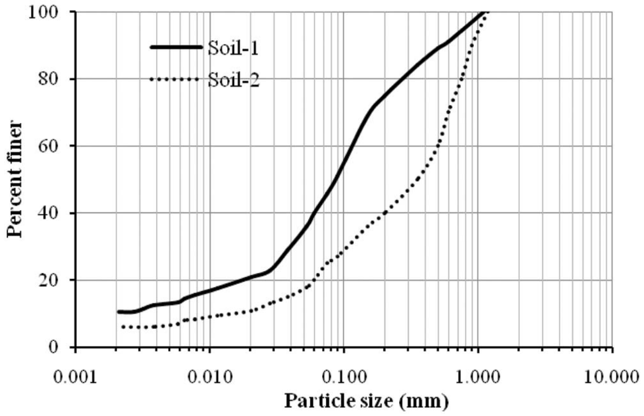

Figure 2. Grain size distribution cures for soils.

Table 1. Characteristics of the soils (OMC: optimum moisture content)

	Soil composition (%)			
Soil designation	Sand fraction	Silt fraction	Clay fraction	Standard proctor OMC (%)
Soil-1	55.0	35.0	10.0	14.3
Soil-2	75.0	22.0	3.0	12.9

Two soils were selected to generate force–deflection relationship of the soil mass. These soils are designated as Soil-1 and Soil-2. Figure 2 shows the grain size distribution curves for these two soils. The characteristics of these soils are given in Table 1. It is clear from the table that Soil-1 has 10% clay and 55% sand, whereas Soil-2 has more sand (75%) and less clay (3%).

Force–stroke relationships were obtained for these two soils. The test procedure to generate force–stroke relationship is as follows:

(a) Soils were mixed with the respective standard proctor optimum moisture contents.
(b) A metal mould of size 305 × 144 × 160 mm (length × width × height) was loosely filled with processed soil.
(c) Soil filled mould was positioned under the piston/plunger of the Universal Testing Machine.

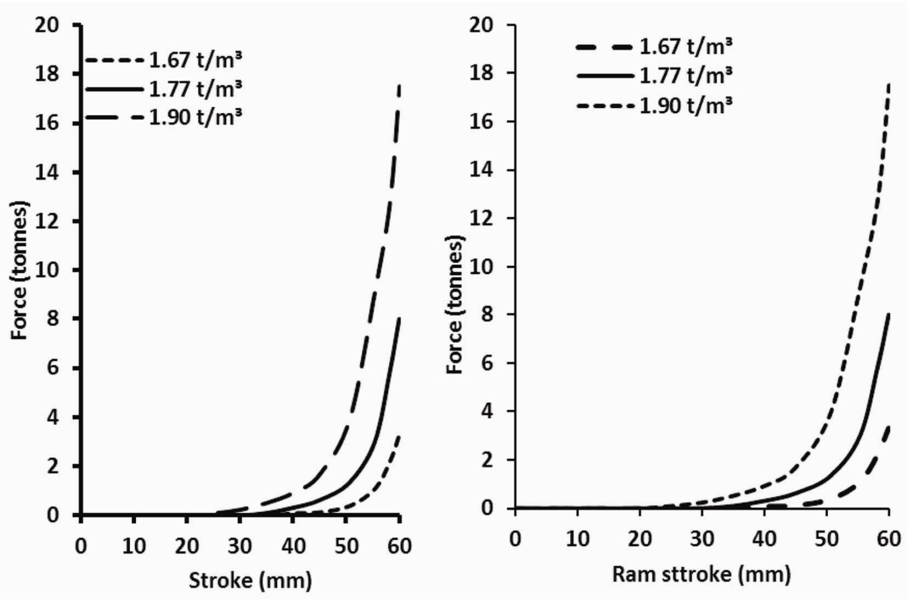

Figure 3. Force–stroke relationships (left, for Soil-1; right, for Soil-2).

(d) The loosely filled soil was compacted by allowing the plunger to move downwards. The force and the corresponding stroke/deflection of the plunger were measured. The plunger was stopped when it moved by 60 mm. Thus the stroke length is 60 mm.
(e) The test was carried out for different values of the initial soil mass, to ascertain the relationship between density and the magnitude of the compaction force.

Figure 3 shows the force–stroke relationships for different initial soil mass for the Soil-1 and Soil-2 respectively. These figures reveal several features of static compaction of soils.

(a) A stroke length of about 60 mm is essential to produce 100 mm thick soil block.
(b) The compaction force increases slowly in the beginning but attains very large values at the completion of the stroke.
(c) The force required for compaction increases with increase in density of soil mass.
(d) The sandy soil (Soil-2) used in the test needs nearly 3 to 4 times the maximum compaction force needed for less sandy soil such as Soil-1.
(e) For the two cases using different soils, the maximum compaction force varies between 1.4 tonnes (Soil-1 with dry density of 1.65 t/m^3) to 17.0 tonnes (sandy soil, Soil-2 with dry density of 1.9 t/m^3).

These tests clearly reveal that the range of forces needed for different soils will vary over wide limits. It may be difficult to compact sandy soils (such as Soil-2) to higher densities in the manual machines, as the compaction force needed will be very large. The compaction force needed for less sandy soils (such as Soil-1) is much smaller.

Toggle mechanism for manually operated soil block machines

The force–stroke relationships for soils shown in Figure 3 indicate that large force is required towards the end of the compaction stroke. This means that the mechanism for a manually operated machine for the soil block production should be capable of providing gradually increasing force amplification as the compaction proceeds. The toggle mechanism is ideally suited for this purpose, as it has large mechanical advantage that produces a large output force at the end of the stroke. This force increases and approaches infinity as the angle between the links reduces. Toggle mechanisms are used extensively for manually operated tools and clamps where a large force is required[10].

There are two types of toggle mechanisms: (a) the toggle mechanism and (b) the reverse toggle mechanism. Figure 4 shows line diagrams for the toggle mechanism and reverse toggle mechanism. The links AB and BC are two main links of the mechanism, and AD is the lever through which the force is applied manually to generate large forces at C. When the lever AD occupies the position AD′, the point C moves to C′, thereby AB and BC will be in one straight line. The point C is hinged to the bottom of the mould in the machine. As the lever AD is pulled down, the point C moves upwards, and the stroke length CC′ is responsible for the compaction of soil in the mould. The mechanical advantage of the toggle mechanism is the ratio of the angular velocities of point C and point B.

Mechanical advantage of the toggle mechanism

Let ϕ_0 and θ_0 be the initial angles (Figure 4). The maximum value of the stroke length CC' depends on the initial

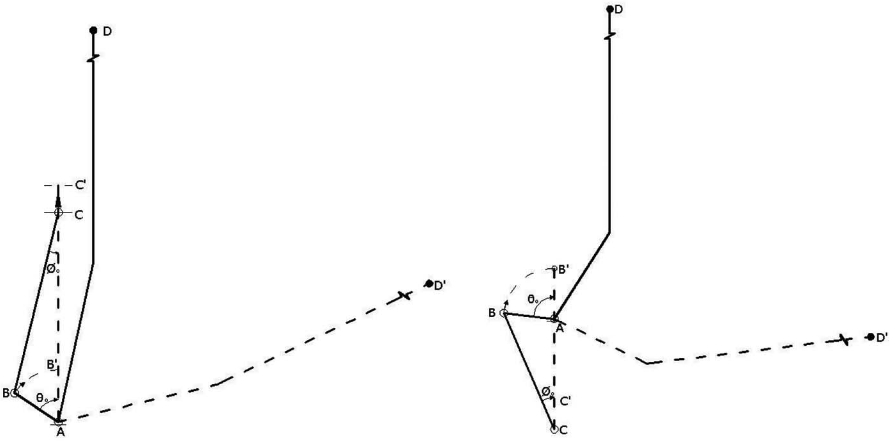

Figure 4. Toggle mechanisms of soil block machines (left, toggle link; right, reverse toggle link).

value of angle θ. As θ approaches zero, the point C moves to C'.

Let $CC' = X_{\mathrm{m}}$ = maximum stroke length.

The expression for mechanical advantage is $A_{\mathrm{T}} = \left|\frac{L\dot{\theta}}{\dot{X}}\right|$ (1)

Then

$$A_{\mathrm{T}} = \frac{L}{r\sin\theta\left[1+\frac{\left(\frac{r}{l}\right)\cos\theta}{\left\{1-\left(\frac{r}{l}\right)^2\sin^2\theta\right\}^{1/2}}\right]}. \tag{2}$$

Asymptotic behaviour of A_{T}

As $\theta \to 0$, $\sin\theta \to \theta$, $\cos\theta \to 1.0$,

$$\lim_{\theta\to 0} A_{\mathrm{T}} = \frac{L}{r\theta\left(\frac{r}{l}+1.0\right)}. \tag{3}$$

Again as $\theta \to 90°$, $\sin\theta \to 1.0$, $\cos\theta \to 0$,

$$\text{and } A_{\mathrm{T}} \to \frac{L}{r}. \tag{4}$$

The value of θ varies between the initial angle θ_0 and zero. It is clear from the eq. (3) that, to achieve maximum amplification towards the end of the stroke (i.e. when $\theta \to 0$) the r/l ratio should be close to zero. Hence, to keep 'A_{T}' large for a given value of θ, L/r should be large and r/l should be close to zero. In practice it is difficult to have exceedingly small r/l ratios.

Mechanical advantage of the reverse toggle mechanism

The mechanical advantage of reverse toggle link is

$$A_{RT} = \left|\frac{L\dot{\theta}}{\dot{X}}\right|$$

Then

$$A_{\mathrm{RT}} = \frac{L}{r\sin\theta\left[\frac{\left(\frac{r}{l}\right)\cos\theta}{\left\{1-\left(\frac{r}{l}\right)^2\sin^2\theta\right\}^{1/2}}-1.0\right]}. \tag{5}$$

Asymptotic behaviour of A_{RT}

As $\theta \to 0$, $\sin\theta \to \theta$, $\cos\theta \to 1.0$, $\sin^2\theta \to 0$.

$$\lim_{\theta\to 0} A_{\mathrm{RT}} = \frac{L}{r\theta\left(\frac{r}{l}-1.0\right)}. \tag{6}$$

Again as $\theta \to 90°$, $\sin\theta \to 1.0$, $\cos\theta \to 0$.

$$\text{and } A_{\mathrm{RT}} \to \frac{L}{r}. \tag{7}$$

In this case also the value of θ varies between the initial angle θ_0 and zero. The eq. (6) describes the behaviour of A_{RT} as θ tends to zero. For a particular value of θ, 'A_{RT}' will be large if L/r is large and if r/l is close to 1.0.

The eqs (3) and (6) clearly indicate that, for particular values of θ, L and r/l, the reversed toggle will always have a better amplification than the toggle mechanism.

Machines for soil block production

Force amplification versus the stroke length for the two types of toggle mechanisms was computed and plotted in Figure 5. The figure shows the relationships for both toggle and reverse toggle links with the assumed values given in Table 2.

Considering the details of the mechanisms given in Table 2, two machines were designed, which are designated as toggle press and reverse toggle press. Both the presses were designed to produce a SSB of size 305 × 144 × 100 mm with a constant stroke length of 60 mm. Figure 6 shows these soil block machines. Both the machines produce blocks of constant thickness because they have a constant stroke length of the piston.

The magnitude of force to be applied at the end of the lever to produce a soil block having dry density 1.85 and 1.90 t/m^3 using toggle and reverse toggle machines is shown in Figure 7. The maximum effort needed for block compaction using Soil-1 and Soil-2 (sandy soil) is displayed in the figure. The force/energy required to compact the block has to be supplied by the human effort during block production process. It is clear from the figure that to achieve a block density of 1.9 t/m^3 with sandy soil (soil 2) the human effort required is about 160 kg and 105 kg using toggle and reverse toggle links respectively. Whereas for Soil-1 to achieve a density of about 1.85 t/m^3 for the block the peak effort required is much lower at about 30 and 20 kg using toggle and reverse toggle links respectively.

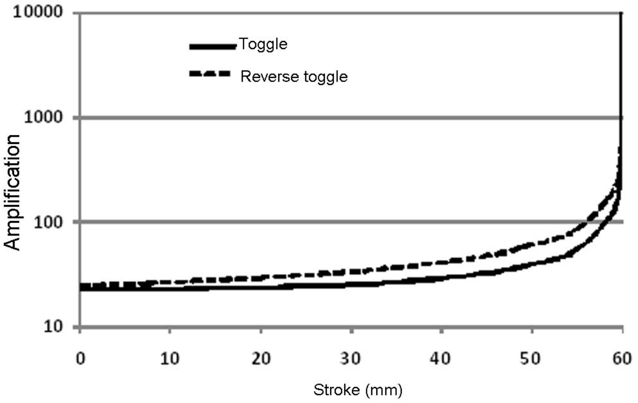

Figure 5. Force amplification versus stroke length in manual soil block making machines.

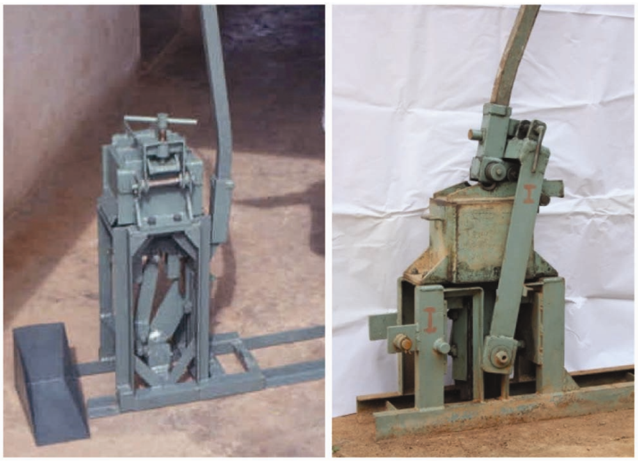

Figure 6. The toggle press (left) and the reverse toggle press (right).

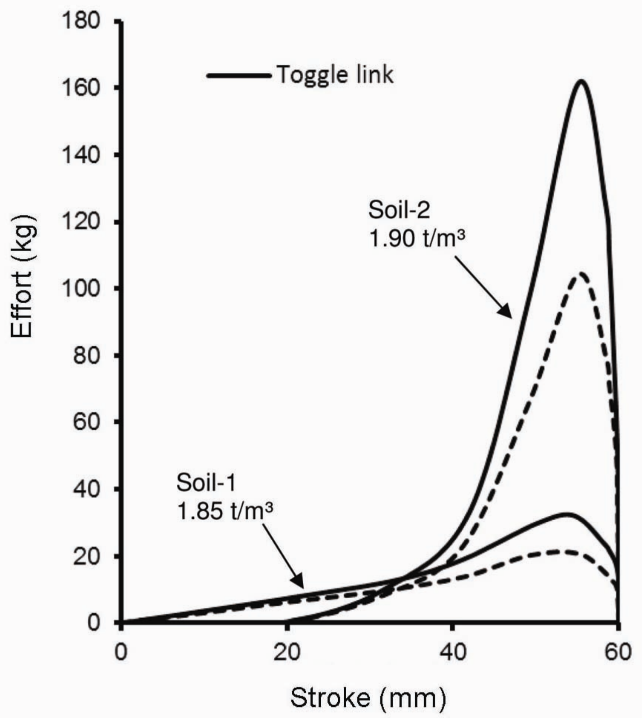

Figure 7. Human effort variation during pressing of a soil block.

Figure 8. SSB block production using manual machine.

Table 2. Details of mechanisms

Type of mechanism	Maximum stroke length X_m (mm)	Initial angle θ_0	(r/l) ratio	Amplification at 50% stroke	Amplification at 75% stroke	Amplification at 95% stroke
Toggle	60	75.52	0.25	26	33	70
Reverse toggle	60	75.52	0.25	34	48	110

Table 3. Time duration for various block making activities

Activity	Average time required
Mixing and preparing soil (for one batch of 25 blocks)	
(a) One person	31 min
(b) Two persons	26 min
(c) Three persons	22 min
Block making	
(a) Loading the scoop	7.6 sec (3.34)
(b) Filling the machine mould	14.7 sec (4.71)
(c) Lid closing and compaction	8.1 sec (3.41)
(d) Lid opening and ejection	7.3 sec (3.57)
(e) Stacking the block	14.0 sec (3.33)

Block size: 305 × 144 × 100 mm; standard deviation values in parenthesis.

Soil block making using the manual machines

The block-making activity using a manually operated machine involves sequence of activities as follows. (a) Preparing/mixing the soil, (b) Loading the scoop, (c) Filling the machine mould, (d) Lid opening and ejection and (e) Stacking the block.

The block making process using a manually operated machine was monitored at a construction site where the SSB's were produced at the site. Figure 8 shows the block-making operation in progress at a site. The time needed for each activity of the block making is given in Table 3.

The block manufacturing is generally done in batches, where each batch operation consists of (i) mixing/preparing an amount of soil for 'n' blocks and (ii) making the blocks in the machine. These can be parallel operations. The batch operation is needed for the following reasons.

(a) If the soil contains Portland cement as stabilizer, the batch of mixed soil should be compacted within the initial setting time of cement.

(b) In manual mixing process it is difficult to achieve a good intimate mix with large quantities of soil.

The total production of blocks per day depends on the number of persons working at the machine and the number of persons preparing the soil. Figures 9–11 show the activity networks and labour utilization diagrams for various combinations of persons working at the machine. Figures 9 and 10 show the activity network and labour utilization diagrams for making *one* block with two and three persons respectively. When two persons are making blocks, there are no parallel activities, and the total time needed for making *one* block is more (51.7 sec). When three persons are involved some of the activities are carried out in parallel and time taken per block comes down to 30.1 sec. Figure 11 shows the activity network and labour utilization diagram for making *one* block when four persons are working at the machine. There are some parallel activities here, but even then the total time needed for making *one* block is 30.1 sec. The labour utilization with four persons at the machine is not as efficient as with three persons.

Figure 12 shows the activity networks for making one batch (25) of blocks for various combinations of persons working at the machine and preparing the soil. The activity networks clearly indicate that, in general, the time needed for making one batch of blocks (25) is less than the time required for preparing the soil for that batch. The total time needed for completion of the batch operation is hence controlled by the soil preparation activity.

Making use of the above mentioned networks, the total production of blocks per day and block production per day per person was calculated and shown in Figure 13. The figure clearly shows influence of number of persons working at the machine on productivity. The number of blocks per person is maximum (125) when three persons are working. It must be noted that even here, the machine is idling most of the time since the soil preparation activity determines the rate of block production. On examining Figures 9–12, it can be seen that the machine is capable of producing about 960 blocks per eight hour working day (30.1 sec per block) when three persons are working at the machine. The productivity capacity of the machine is high and it needs to be provided with prepared soil at the same rate for better capacity utilization. In the event of more efficient soil preparation, the productivity of the manual machine could be more than doubled.

Case studies: production of stabilized soil block and their use in housing projects

SSB technology has been used for the construction of buildings and there are a number of structures in India. The technology has been conveniently exploited for the construction of buildings in rehabilitation programmes after natural disasters in India and elsewhere[9,11]. In such

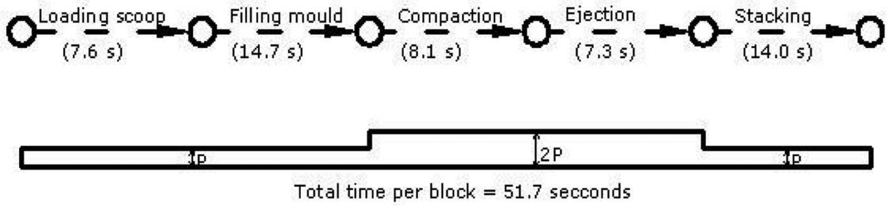

Figure 9. Activity network and labour utilization diagrams for making *one* block with two persons (P: person).

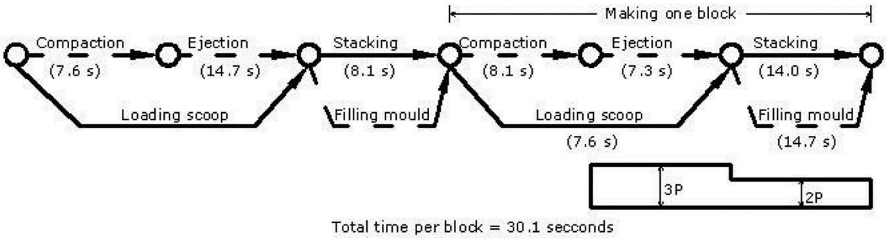

Figure 10. Activity network and labour utilization diagrams for making *one* block with three persons (P: person).

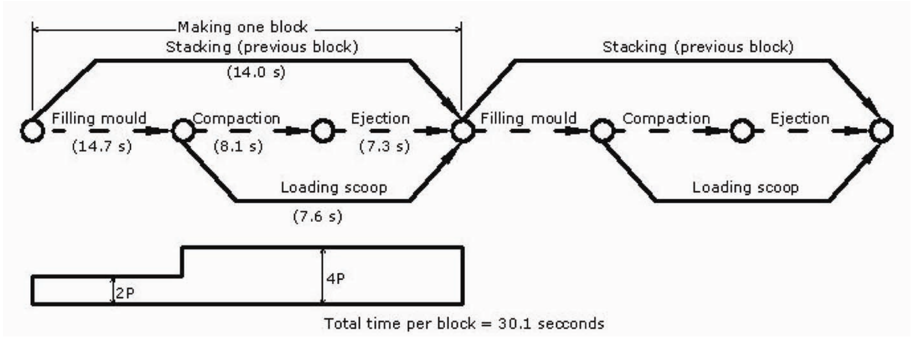

Figure 11. Activity network and labour utilization diagrams for making *one* block with four persons (P: person).

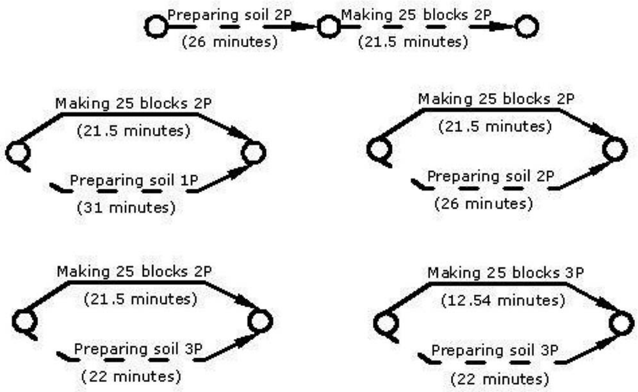

Figure 12. Activity networks with different number of persons with the machine and soil preparation (P: person).

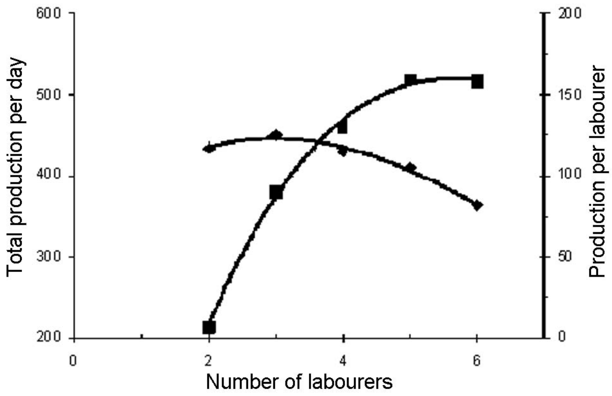

Figure 13. Block production per day and production per person.

rehabilitation programmes SSBs were produced using manually operated machines in a decentralized manner. Currently, a large project, called Good Earth eco-homes involving, is commercial venture intended for middle and high income group families. Details of this case study have been provided below. These blocks were also used to build homes in an earthquake devasted Bhuj, the details of which are provided below.

Bhuj earthquake rehabilitation project

A team comprising of 10 people were able to produce 800 blocks per day for a housing project aimed at rehabilitating the earthquake devastated Bhuj in Guajarat during the 2001 earthquake. In association with Hunnarshala foundation based in Bhuj (India) construction of more than 4000 SSB houses in and around Kutch region of Gujarat

Figure 14. Block making and stabilized soil block houses.

Figure 15. Compacted stabilized fly ash block production at construction site and the houses built.

in India was undertaken within a span of two years. Figure 14 clearly shows a cluster of houses that are being constructed using SSB masonry.

Tsunami rehabilitation project

Using the SSB masonry technology, 140 houses were built in Kodaiyampalayam village in Tamil Nadu, which was stuck by a tsunami. Figure 15 shows the block production and the houses built.

Good earth eco-homes project

Currently a large project involving production of over 3 million SSB is under construction. The project is located in the outskirts of Bangalore city limits. This project is a commercial venture intended for middle and high income group persons. Figure 16 shows cluster of houses in this housing project where 400 dwellings are planned using SSB masonry in four phases. The houses have load bearing SSB masonry walls. About 200 houses have been completed in two phases. The SSB's were produced by employing ten numbers of manually operated machines. Figure 16 shows block production and stack of blocks in one of the block making units at the construction site. The manual machines were carted to different places in the project construction site where the blocks are required. SSB's were consumed at the place of production without much transportation. These operations are clear examples of decentralized block production systems.

In each block production team, eight persons work on one machine. Soil preparation and block production are parallel activities. All the activities are manual. The distribution of persons for various block making activities in a team is as follows. (a) Soil preparation (including sieving) – 3 persons, (b) Block making activities at the machine – 4 persons and (c) Curing the stack of blocks – 1 person.

Figure 16. SSB production at site and SSB masonry houses.

Prepared soil is made available continuously such that the block production takes place without idling the machine. Here, the block production per day per team is in the range of 700–800 blocks. In a span of about two years, the ten block making teams have produced over three million SSBs.

Conclusion

This paper discussed static compaction of soils, analysis of toggle mechanisms, design of manually operated soil compaction machines, analysis of decentralized stabilized soil block production systems, time and motion study of manually operated block production systems, critical network analysis using CPM technique, and three case studies involving large-scale production of blocks using decentralized production systems have been discussed. The studies demonstrated the following:

(1) The force required for compaction of highly sandy soils is an order of magnitude higher than that required to compact clayey soils. The effort needed for compaction reaches maximum when 90% of the stroke has been completed.

(2) Toggle mechanism is ideally suited for the manually operated soil compaction machines employed for the production of soil blocks. Reverse toggle link is more efficient than the toggle link in reducing the compaction effort required for soil block compaction.

(3) The manually operated machines are capable of producing two blocks per minute provided the processed soil is supplied continuously. The study reveals that soil processing is a controlling factor in block production.

(4) The block (size 305 × 144 × 100 mm) production using manual presses can be as high as 800–900 blocks per day with a per capita production of 125 blocks per day.

(5) The manual machines are very effective in generating employment at lower capital cost.

(6) The manual machines can be successfully employed to produce large requirement of blocks in a construction site by carrying out the block production in batches at different places simultaneously.

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