

Mechanization and Performance Analysis of Vertical Slip Form Wall Construction Technology

H.P. Hemantha Kumara and G.K.K.A. De Silva

Abstract: Building construction industries in Sri Lanka are currently facing burning issues due to lack of construction materials, transportation and high labour cost. Masonry wall construction and plastering is one of the most important jobs of small and large building construction.

The slip form technology is an alternative wall construction method, introduced to the Sri Lankan construction industry in 1980, instead of burnt clay brick walls or cement sand block walls. The conventional slip form wall construction technology was commenced by the National Engineering Research & Development Centre (NERDC) with a fully manually operated system consisting of steel shutters, yokes, hydraulic jacks, and manually operated compaction hammers. An amount of 10% cement with quarry dust mix volume is sufficient to get required strength (cement quarry dust ratio is 1: 10) and it can be used as a load bearing wall between columns. The system has identified main drawbacks while construction of a wall such as uneven compaction due to manual compaction, high operational and shutter lifting time etc.

NERDC has been studying and developing a mechanized slip form wall construction machine in order to promote this technology in the society. The machine consists of a single phase 230 V hydraulic power unit, two slip form shutters, two lifting hydraulic cylinders and a movable vibrator compaction unit. Cement quarry dust mixer compact between columns by vibrating and applying a maximum of 140 kg static load by a hydraulic cylinder. Shutter lifting total vertical force measured is 620 kg with overcoming friction between metal shutter and newly bonded wall. Compaction ratio obtained was 40% to 45% varying with moisture content of a mixer. Average wall construction rate is around 75 to 80 min/m. A standard 140 mm diameter cylindrical core was tested with the test results for 150 mm thick and 2900 mm span wall showing an average strength of 4.9 N/mm² after 28 day completion of wall. The average shutter lifting speed was measured as 24 mm/second. The machine was tested up to 10 feet wall height continuously. The tactile controlled basic hydraulic system was employed to improve better man machine interface with the entire operation. High initial setting time and heavy weight are the main drawbacks identified while operating the system with three operators. It is likely that four operators are required to achieve a better performance from the system.

Key words: Slip Form, Vibration, Compaction, Tactile controller

1. Introduction

The wall is a main component of any building and carries out important functions such as bearing loads, provide fire protection, heat and sound insulation, and provide protection against environmental and weather conditions. Wall is also used as a partition of interior spaces [1]. Different kinds of masonry materials have been used for the construction of building walls in Sri Lanka. Burnt clay bricks and sand cement blocks are typically used. The main drawbacks of using conventional clay bricks are lack of clay, low strength, and high production cost and time.

Low quality bricks affect the strength of the building walls. Low strength and high variability are the reasons why it is difficult to select clay bricks for load bearing wall construction. In that case, hence, walls are being constructed in a concrete frame due to non-

assurance of masonry engineering wall strength. Further, masonry brick walls cannot be constructed and plastered continuously due to lack of adequate strength to steady the wall.

Generally, the construction is carried out in stages with construction discontinuing after a particular period once built-up to 1.5 m height to allow strength gain. At least 4 days are required to complete the wall with plastering [1]. hemantha@nerdc.lk, ari@nerdc.lk

*Eng. H.P. Hemantha Kumara, MSc, CEI I&II, AMIE (SL)
Senior Research Engineer, National Engineering Research and Development Centre of Sri Lanka, Ekala, Ja-Ela.
Email: hemantha@nerdc.lk
ORCID ID: <http://orcid.org/0000-0003-0311-6458>*

*Eng. G.K.K.A. De Silva, BSc Eng(Civil), MSc, C.Eng, MIE(SL), Deputy Director General (R&D), National Engineering Research and Development Centre of Sri Lanka, Ekala, Ja-Ela.
Email: ari@nerdc.lk
ORCID ID: <http://orcid.org/0000-0001-7051-0012>*



However, findings have been made to introduce new bricks, such as cement blocks, compressed soil blocks and cement-ash mixed bricks, for building wall construction.

Soil blocks are better to construct well finishing both interior and boundary walls. Availability of soil and cost of production are main drawbacks for soil block production. The cement stabilized block is widely used in building construction industries in Sri Lanka.

In early 80's, Kulasinghe [2] first introduced slip form technology as an alternative wall construction method to burnt clay brick walls or cement sand block walls.

The conventional slip form wall construction method is fully manually operated, and system has identified several drawbacks while constructing a wall, such as uneven compaction due to manual compaction, high compaction and shutter lifting time etc.

As a solution to this problem, NERDC has developed a mechanized slip form wall construction machine to promote this technology in the construction industry. The mechanized machine operates well with minimizing operational time. Greater initial setting time and the heavy weight are the main drawbacks that were identified while operating the system with three operators. Most likely, four operators are required to achieve a better performance from the system.

2. Slip Form History and Types

Slip form techniques consist of forming panels, yokes and jacks. There are two types of slip form constructions [6], viz., horizontal and vertical.

Horizontal Construction

It is a process which is used to consolidate form into a geometric shape appropriate for larger jobs that require high production rates.

Vertical Construction

In vertical slip forms, mixture is continuously placed, compacted and form work is pulled up. Rate of slipping of formwork depends on the feeding speed of cement quarry dust mixer, moisture content and rate of compaction. This method is suitable for uniform shaped rapid construction. Various methods of moving and lifting sectional forms were tried. The method used by Peavey in 1899 employed a system of

steel angle frames and yokes to maintain the spread and shape of the forms, while a lifting force was applied to the forms by hand-operated locomotive screw jacks located on top of previously hardened wall [3]. Figure 1 provides a sketch of the Peavey system.

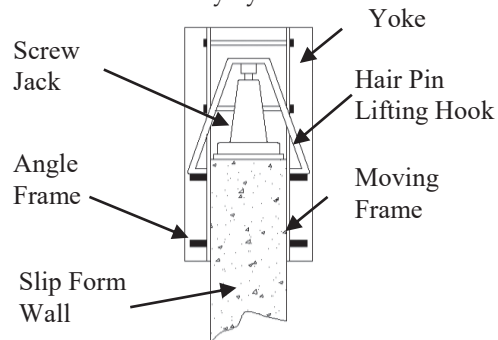


Figure 1 - Peavey Slip Form Wall Construction System

The first true slip form system was developed in 1903, when contractors began supplying lifting power to the forms by screw jacks positioned outside the form through the use of wooden jacking legs. Such a system is shown in Figure 2.

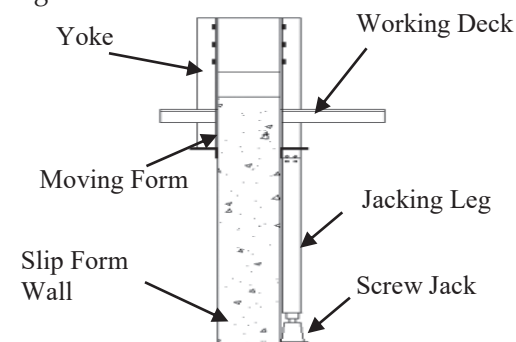


Figure 2 - First True Slip Form System

Several additional lifting systems were devised, and by 1910, the most commonly used system consisted of a hand-operated hollow screw jack, which climbed a steel rod or a hollow pipe, that was subsequently left in place in the completed concrete wall. Figure 3 illustrates such a system.

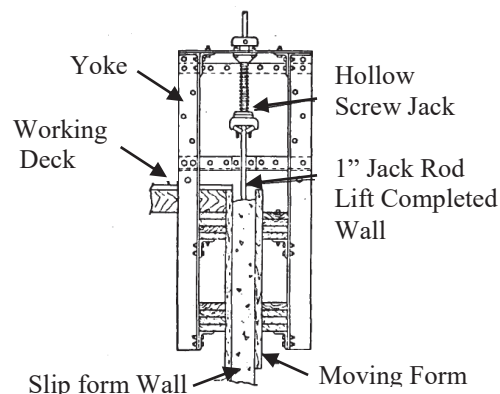


Figure 3 - Hand-operated Hollow Screw Jack Operated Slip Form System

Thus, vertical slip forming is an extrusion process where the material is stationary and the form moves upward.

The actual median form speed however, depends on such factors as admixtures used, type of the cement, water cement ratio and cement quarry dust content, symmetry of the structure being constructed, required variations in wall thickness, amount and complexity of placement, jack spacing, number of blackouts required, and the depth of the forms.

3. NERDC Slip Form Technology

The conventional NERDC slip form wall construction system consists of yokes, frame and shuttering assembly.

Yokes provide two primary functions: to keep the forms from spreading; and to transfer the load of the forms to the jack [2] [4] [5]. Yokes are inverted U shape, consisting of two legs and a cross beam. The legs are attached to the frame and carry the vertical loads in tension, and the lateral loads as cantilever beams. The cross arm of the yoke must be designed as a simple beam supported at the centre by the jack and subject to the moments from both the vertical and lateral leg loads. Yoke spacing depends on several factors, including the design loads of the yoke and wales, and the lifting capacity of the jacks attached to the yokes. Conventional slip-forming systems employ 2 ton capacity hydraulic jacks. The frame provides support and holds the shuttering in position, suspended scaffolding and transmit the lifting forces from the yokes to the form system.

The shutters make up the sides/walls of the forms and are the portion of the formwork which actually contains and shapes the wall. Since slip-forms are subjected to the hydrostatic pressure of the plastic masonry mix, the shutters must support this lateral pressure with beam action between the wales, and as a cantilever at the bottom of the form. The friction or drag force on the forms during the sliding action is significant. This loading is highly variable and depends not only on the type and depth of shutter used, but also on the temperature, moisture content, workability, and rate of concrete set. Steel forms are more rugged, smoother, and easier to clean, but they do not lend themselves to easy alteration or repair during the slip operation.

A conventional NERDC slip form shutter assembly fixed between two columns by means

of yoke assembly is shown in Figure 4. Note that there are no supports to keep wall thickness at mid span. If, in the case, deformation occurs at mid span of the wall, wall strength will reduce.



Figure 4 - NERDC Conventional Slip Form Wall Construction Technology

The wall strength is analysed by 140 mm diameter core testing according to BS1881 standard. Figure 5 shows the compressive strength variation of the whole wall span. According to the test results, wall strength obtained is low at mid span of each sample.

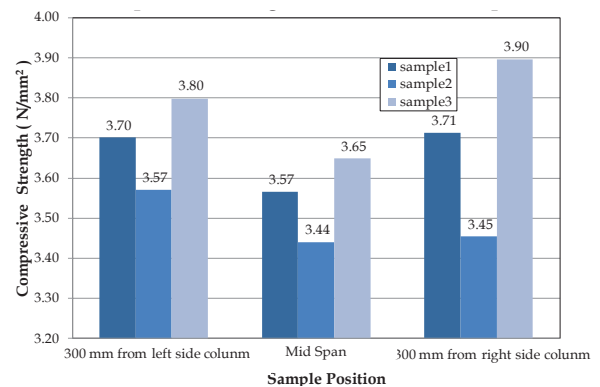


Figure 5 - Compressive Strength Variation Across the Wall Span

Uneven compaction

While compaction of mortar between shutters, uneven compaction could occur due to manually operation of impact hammer. The impact hammer consists of a force applied by foot and sliding mass component. It is practically difficult to maintain the hammering unit in a vertical position during compaction of mortar. It causes variation of wall strength across the total span. Random observations indicate the manually compaction rate to vary from 35% to 45%.

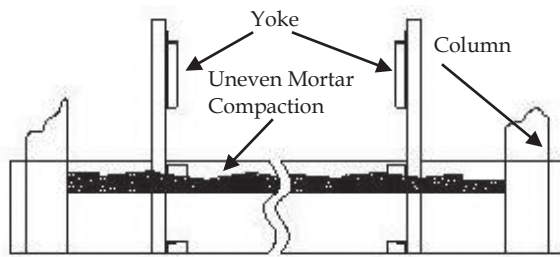


Figure 6 - Uneven Compaction Pattern of Manual Impact Hammering

The average shutter lifting speed obtained is 5.7 mm/second and average compressive strength measured after 28 days is 3.6 N/mm².

4. Mechanization of the System

This paper presents a new slip form wall construction system to mechanize the existing manual system and it consists of a vibration compact unit, yoke with hydraulic cylinders for lifting the shutters, two shutters, a portable hydraulic power unit and valves.

With the mechanized system, mixing and filling of mortar is done manually and compaction is done by the vibrator unit and the shutter lifting process done by two hydraulic cylinders.

The hydraulically operated mechanized slip form wall construction system improved the wall construction rate by several times over existing manual system without increasing labour involvement. Further, it increased 1.5 times strength of 150 mm thick wall compared with the conventional system. The proportion of cement to quarry dust ratio can be increased from 1:10 to 1:12, which saves usage of cement by an adequate amount but maintaining the standard required strength of the construction wall.

A - Form shutter, B - Yoke, C - Compaction unit, D - Vibrators, E - Hydraulic motor, F - Lift control valve, G - Move control valve H - Static load control valve, I - Hydraulic power unit, J - Hydraulic hoses , K - Level indicator

5. Slip Form Wall Construction

The mechanized system was fixed to a 10 feet span 6" x 6" precast column which was erected at site, early. The cement to quarry dust ratio 1:10 mixed masonry materials were used. Usually 0.5 water cement to 0.65 ratio was practically identified as better to maintain this construction.

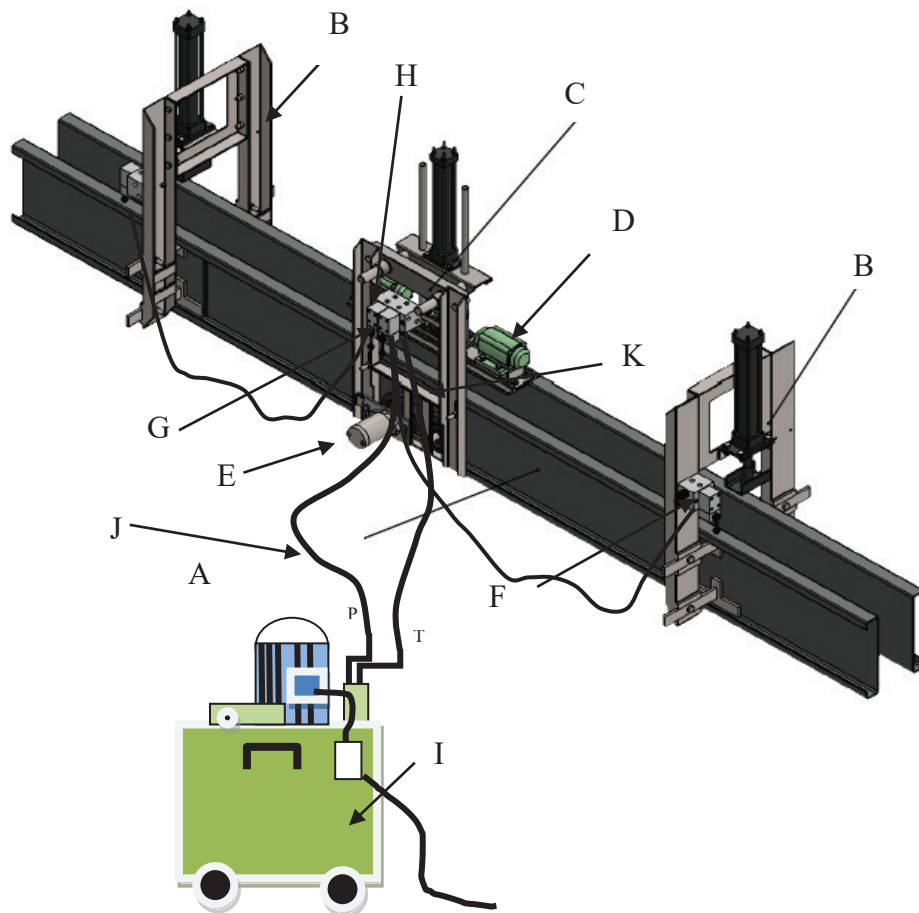


Figure 7 - Mechanized Slip Form Wall Construction Machine and Components

The mortar was filled between the two shutters and levelled. Mortar was compacted using the vibrator unit by applying a static load. The compaction time and applied static load were controlled by the machine operator while compacting 200 mm height freshly filled mortar to 100 mm of finished wall. After attaining the required compaction, shutters were lifted to the next layer. Therefore, in order to obtain 10 feet full wall height, it was necessary to repeat the process.

6. Vibratory Compaction

6.1 Compaction

Compaction is defined as the method of mechanically increasing the density of mortar.

Compaction of mortar to the required degree is a very essential aspect of continuous masonry construction. Strength, surface finishing of the wall and constructability mainly depend on the degree of compaction. There are four types of compaction effort on masonry construction such as vibration, impact, kneading and pressure. The two principle types of compaction forces were identified as static and vibratory. Static force is simply the deadweight of the machine, applying downward force on the mortar surface and compressing the mortar particles. The only way to change the effective compaction force is by increasing or reducing the weight of the machine. Static compaction is confined to upper mortar layers and is limited to any appreciable depth.

The controllable static load of the system, applied by compressive spring loaded hydraulic cylinder with tactile controlled manual valve, is shown in Figure 8. Figure 9 shows the static load variation with time during mortar compaction.

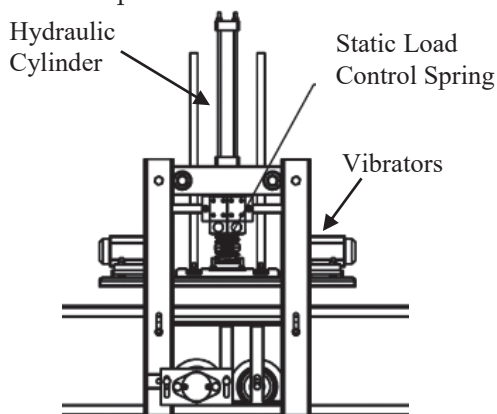


Figure 8 - Vibratory Mortar Compaction Unit with Controllable Static Load Application

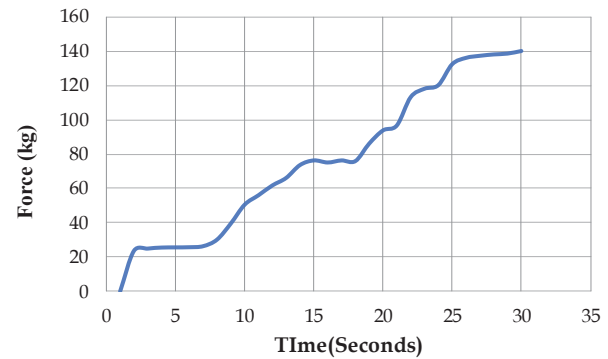


Figure 9 - Quasi Static Load Variation with Time during Mortar Compaction

The motor driven vibrating mechanism (230 V, 50 Hz) is usually a rotating eccentric weight or piston/spring combination with a 35 kg vibration force and 2.5 mm amplitude. The compactors deliver a rapid sequence of blows (impacts) to the surface, thereby affecting the top layers as well as deeper layers. Vibration moves through the material, setting particles in motion and moving them closer together for the highest density possible. Based on the materials being compacted, a certain amount of force must be used to overcome the cohesive nature of particular particles. Figure 10 and Table 1 shows the practical density variation of mortar due to use of various compaction techniques.

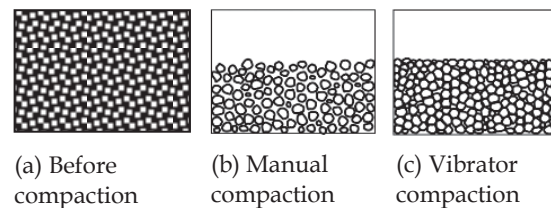


Figure 10 - Density Variation with Different Compaction Methods

Table 1 - Density measurements due to different compaction techniques

a	b	c
1153.3 kg/m ³	1965.2 kg/m ³	2226.1 kg/m ³

Most granular mortar mixes with a content of fines (particles < 0,064 mm) less than 10% can be compacted by vibratory and impact methods.

6.2 Energy transfer from compaction foot

In the plastic zone at the interface between the mortar and the compaction foot, the maximum shear stress can approximate by Equation 1[6].

$$\tau_f = v_{\max} Z_s = v_{\max} C_s \rho \quad \dots(1)$$

where, v_{max} is the maximum particle vibration velocity, Z_s is the mortar impedance and ρ is the bulk density. The mortar impedance is the product of the strain dependent shear wave velocity (C_s) and the soil density (ρ). According to Equation 1, the maximum vibration velocity that can be transmitted to the mortar in the plastic zone can be estimated. The compaction unit can travel horizontally on the shutter assembly by operating the hydraulic motor with a speed of 300 mm/sec.

7. Case Study

7.1 Influence Factors

Batterham [6] reported on a series of tests which investigated the lateral and friction forces acting on vertical slip forms. The various influence factors involved were divided into two general groups. Group One Factors were defined as the controllable variables such as general formwork design, wall thickness, slide speed, type of formwork facing, mortar compaction (vibration) and wall consistency (slump). The Group Two Factors were the uncontrollable influence factors, which included live loads and differences in travel of the lifting gear. Therefore, it was assumed that the pressure head on the form was directly related to the rate of slide. To a very limited extent, the thickness of the completed wall was also related to the rate of slide. Forces transmitted to the wales were pre-calculated, to allow for correct separation of the vertical and horizontal forces.

7.2 Lifting of Shutters

The yoke and hydraulic lifting cylinder unit consist of frame, hydraulic cylinder, and pressing foot attached to the piston of hydraulic cylinder. The purpose of this unit is to lift the set of form shutters after compaction of previous layer of the wall. When the hydraulic cylinder is operated by hydraulic valve, the pressing foot connected to end of the piston rod exert a downward pressure on top of the wall, and as a result, frame and set of form shutters slide vertically up along two columns. To ensure the horizontal alignment of the form shutters, two units of this type have been installed in the system close to two columns.

7.3 Test Results

The data resulting from the series of tests conducted is given in Table 2.

Table 2 - Load Analysis Test Data for Vertical Slip Form Wall Construction

Lifting speed		24 mm/sec	
Wall thickness		150 mm	
Material		Cement, Quarry dust	
Mixer ratio		1:10	
Water/cement ratio		0.6	
Form work material		Mild steel	
Dead weight of shutters		168 kg	
Friction Load		Min - 254 kg	
		Max - 620 kg	
pressure on the form work (kg/m ²)	Upper Waling	After placing mortar	142 kg
		After Vibration	205 kg
	Lower Waling	After placing mortar	93 kg
		After Vibration	127 kg
		During lifting	134 kg
	Resulting slip form pressure on the lifting frame		387 kg

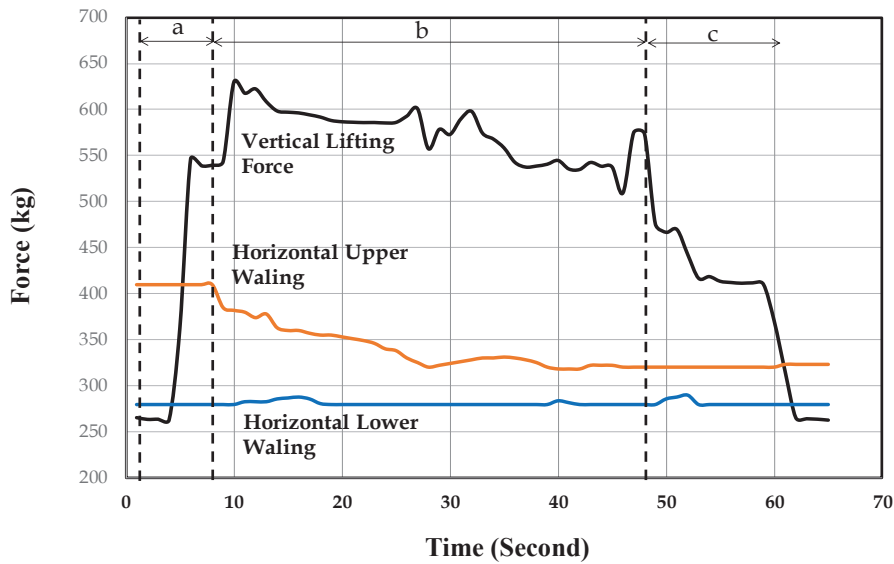
The form shutter vertical lifting force and horizontal frame load were measured using a 2000 kN compressive load cell with Flintec FT-11 Weight Indicator shown in Figures 11 and 12 respectively.



Figure 11 - Vertical Lifting Force Measured by Using Compressive Load Cell



Figure 12 - Slip form Shutter Horizontal Force Measurement



a = Initial frictional loa
 b = Force variation w
 form shutters mov
 period
 c = Dead load of
 shutter components

Figure 13 - Horizontal and Vertical Forces on the Slip Form During Lifting Shutters

The shutter lifting vertical force was increased gradually until shutters move upward, overcoming frictional resistance. Figure 13 shows lifting force variation, upper and lower shutter frame load variation, due to 200 mm high slip form work wall construction.

Figure 13 shows that the vertical forces on the forms are greatest just before the forms overcome surface friction and begin to move. Once the slip form is in motion, the vertical force continues to decrease until the hydraulic pressure in the jacks reaches zero. Further decrease in vertical force is then caused by slippage in the jack lifting head. The remaining vertical force is caused by the weight of form work. Horizontal force in the upper waling decreases during the slide.

The force on the lower waling is relatively constant, reflecting the fact that the mortar has already begun initial set by the time it reaches this lower portion of the slip form. The horizontal forces increased on both wales whenever vibration of the mortar was taking place [6]. The increase was greater with greater depth of vibration. Higher slide speeds than those used in the experiment are common and the resulting lateral pressures under extreme slide speeds will be much greater than those noted in these tests.

The effective head of mortar which in turn determines the lateral pressure on the formwork is influenced by the sliding speed, setting time, form sheathing, and the depth of mortar vibrations. All of these factors except mortar vibration can be controlled. However, well-vibrated mortar is desired in many cases for the increased density and strength produced.

The Batterham method [6] incorporated these facts and the test data to produce an analytical formwork model. Figure 14 shows the general model of lateral pressure distribution on vertical slip forms as a function of formwork depth.

Using Figure 14, Batterham [6] states the following:

$$P_o = H_o + H_U \quad \dots(2)$$

where,
 P_o = Total resultant lateral force
 H_o = Measured lateral force against the upper wale
 H_u = Measured lateral force against the lower wale

Equation 3 evaluates Z_o , which is the distance of P_o from the top of the new mortar [6].

$$Z_o = \frac{0.05H_o + 0.24H_U}{H_o + H_U} \quad \dots(3)$$

This is actually the sum of moments about point A (in meter - kg) divided by the sum of the horizontal forces on the wales (in kg), for a per meter longitudinal length of slip form.

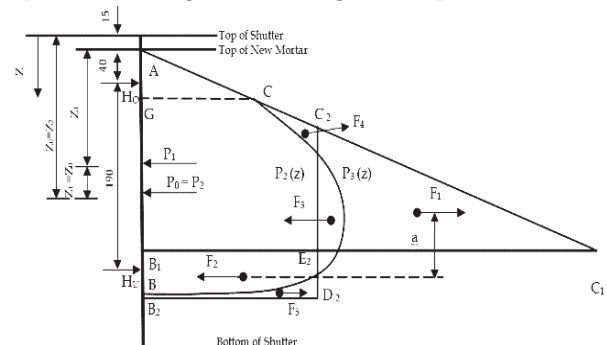


Figure 14 - Batterham Model of Lateral Pressure with Vertical Slip Form Depth



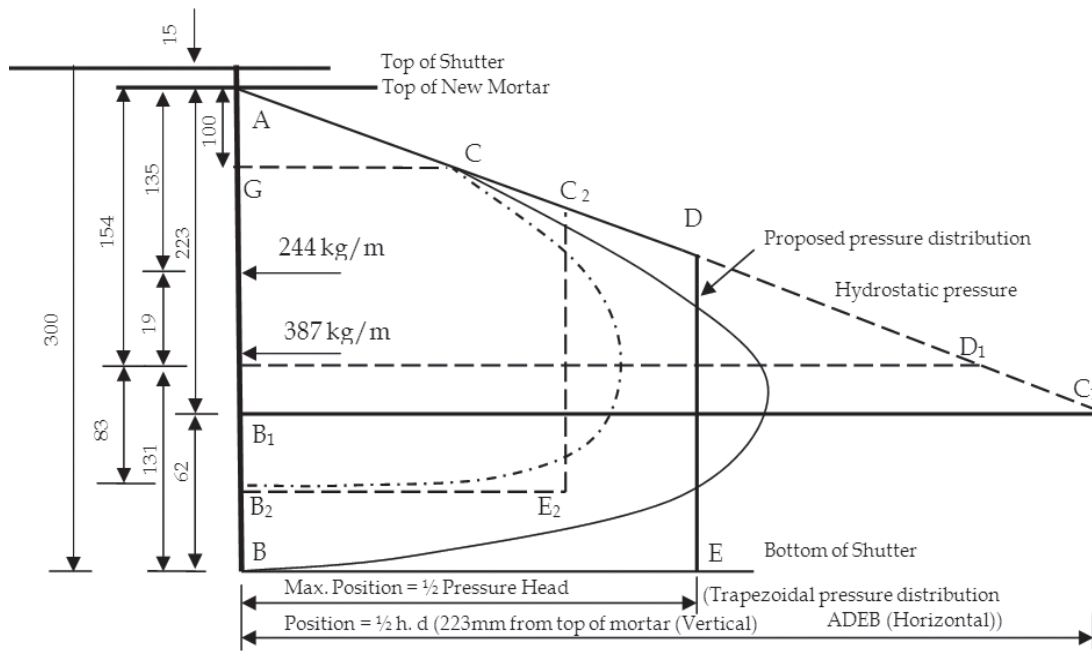


Figure 15 - Maximum Pressure on Vertical Slip form

Point A, which corresponds to the top of the freshly placed mortar, which also corresponds to $j(z) = 0$, and $z = 0$. Hydrostatic pressure of the density on the mortar just placed, represented by $j(z) = p_z$, states that Equation 4 Point B is the point where the mortar and form separate.

Lateral pressure is equivalent to a hydrostatic pressure distribution corresponding to triangle AC_1B_1 with the resultant horizontal or lateral pressure equating to P_1 . P_1 is assumed to be equal P_0 .

$$Z_1 = \sqrt{\frac{2xP_o}{P}} \quad \dots(4)$$

Triangle AC_1B_1 represents the hydrostatic pressure distribution P for mortar that weigh approximately 1153.3 kg/m^3 . The hydrostatic pressure distribution of a level fill vertical masonry wall is given by Equation 5.

$$q = kDh \quad \dots(5)$$

where, q is hydrostatic pressure, D unit weight of masonry materials, h vertical height from top surface of mortar and k is a constant of wall filling condition as given in Equation 6.

$$k = \left[\frac{1 - \sin\theta}{1 + \sin\theta} \right] \quad \dots(6)$$

where, θ is surcharge angle and it becomes zero due to level filled condition. Hence $k=1$ in this application. Second approximation is to assume that the $P_2 = P_o = P_1$ and $Z_2 = Z_o$. The distance of C_2D_2 and D_2B_2 may be determined by the Equation 7 and Equation 8.

$$F_1 = C_2C_1E_2 = F_2 = B_1E_2D_2B_2 = F \quad \dots(7)$$

$$P_1 (Z_1 - Z_o) = F a \quad \dots(8)$$

where,

$$P_1 = P_o$$

$F = F_1 = F_2 =$ forces acting at the area centroids

$a =$ distance between centroids of areas F_1 and F_2 .

Thus, lateral force trapezoid $GCC_2D_2B_2$ may be determined. In Batterham [6] terms the third and most correct approximation, points B and C are connected by a dotted curve such that the sum of forces F_3 , F_4 and F_5 equals zero, and $F_4 + F_5 = F_3$.

Each approximation is successively more realistic, with approximation one as a triangle, approximation two a trapezoid, and approximation three as an area bounded by the formwork and a curve as shown in Figure 14. The lateral force variation model and graphical representation given in Figure 15.

The final approximation curve shows that the mortar and slip form separate at a point B_1 , 238 mm below the top of the formwork. This indicates that the slide speed could have been increased. At the theoretical maximum slide speed, the separation point would coincide with point B.

Batterham [6] recommends that the resulting lateral formwork pressure at point B (at the bottom of the slip form for optimal slide rate) be used as the design load. This can be easily done because the trapezoidal pressure distribution gives an excellent approximation of both the general distribution of lateral pressure and the position of the resultant force, as verified by the test.

Therefore, for the NERDC slip form 300 mm (12 in) deep and with mortar lifts of 100 mm (4 in), the bottom of the force trapezoid is determined to coincide with the bottom of the formwork, and the horizontal width is determined as one half the maximum.

According to the test resultant hydrostatic pressure applied a point 223 mm below the top of the new mortar level. This lateral force distribution can be proportionately applied to all slip form depths. Thus the maximum force trapezoid can be determined by the formwork base, the top of the fresh concrete and a lateral force equal to one half the maximum hydrostatic pressures taken at a depth equal to 2/3 the form depth.

8. Performance Analysis

The mechanized slip form wall was constructed 1.29 m long, 3 m full wall height and 150 mm thick, with 1:10 cement: quarry dust mix in open environment. The wall stability and constructability were tested. The 1:10 cement/quarry dust ratio is used as the practically found optimum ratio for slip form wall construction [2].

The load bearing capacity of this continuous masonry vertical slip form wall was tested using $\phi 140 \times 150$ mm cylindrical cores. Standard specimen cores were cut by core cutting machine as shown in Figure 16.



Figure 16 - Cylindrical Specimen Core Samples Cut by Machine

The prepared specimen cores were tested after 3, 7, 14, 28 and 120 days from slip form wall construction according to BS1881 test standard.



Figure 17 - Compressive Strength Test of Specimen Core Samples

The compressive strengths of tested wall specimens are as shown in Table 3.

Table 3 - Compressive Strength Variation with Different Ages of Sample Wall

No	Age (Days)	Load (kN)	Sectional area (mm ²)	Average Compressive Strength (N/mm ²)
01	3	25.5	13273	1.92
02	7	38.5	13273	2.90
02	14	50.0	13273	3.77
03	28	65.0	13273	4.90
04	120	117.0	15397	7.65

The compressive strengths, compared with mechanized system and other wall construction methods, after 28 days from preparation are shown in Table 4 [7].

Table 4 - Compressive Strength Comparison of Different Wall Panel Types

Ratio	Panel size	Panel Type	Load (kN)	Strength (N/mm ²)
1:7	4"	Brick	67.7	1.23
1:7	9"	Brick	153.3	1.11
1:5	4"	Brick	130.7	2.37
1:5	9"	Brick	213.7	1.66
1:6	4"	Continuous (Cement, Sand)	890.0	11.81
1:8	4"	Continuous (Cement, quarry dust)	748.0	10.39
1:10	4"	Slipform original (Cement, quarry dust mix with coir)		2.13 ~ 3.14
1:10	6"	Slip form NERDC Conventional Cement, quarry dust	48.4	3.64
1:10	6"	Slip form NERDC Mechanize Cement, quarry dust	65.0	4.90

9. Analysis of Failure Mode

There are some critical problems were identified during operation of mechanized slip form constriction machine.

The lifting stress can be divided into static and sliding lifting stresses. Static lifting stress represents the friction that has to be overcome in order to start sliding and the sliding lifting stress is the minimum friction that occurs during sliding. Both the lifting frequency and the lifting height had a considerable effect on the static lifting stresses. Lower lifting height or reduced lifting frequency will both result in a higher static lifting stress [8].

9.1 Lifting Cracks



Figure 18 - Horizontal Cracks Propagate During Shutter Lifting

Horizontal (long) crack propagation on the wall face perpendicular to the lifting direction is normally identified as lifting cracks as shown in Figure 18.

The depth and width of these cracks may vary from thin, shallow to deep, and wide. Lifting cracks are associated with forces during lifting of the slip form panel. Heavy static load and high degree of vibration on the masonry can also make cracks.

Lifting cracks that occur during slip forming have often been assumed to be the main cause for poor quality masonry materials, moisture content and deformed structures.

9.2 Lump Formation

Lump formation starts as a thin layer of grout sticking to the vibration foot. It continues to grow layer by layer until a lump is formed as shown in Figure 19. After the lump hardens, it

causes to damage the top of the newly compressed mortar layer.



Figure 19 - Lump Formation on the Bottom Side of the Vibrator Foot

10. Structural Analysis of Form Shutters

The forming metal shutters have subjected to complex combine stresses during the construction of slip form wall. Hence Solid Works software tool (2016) was used to simulate behaviour of form shutter with static combine loads. Figure 20 shows the combine forces subjected to one side of the form shutter.

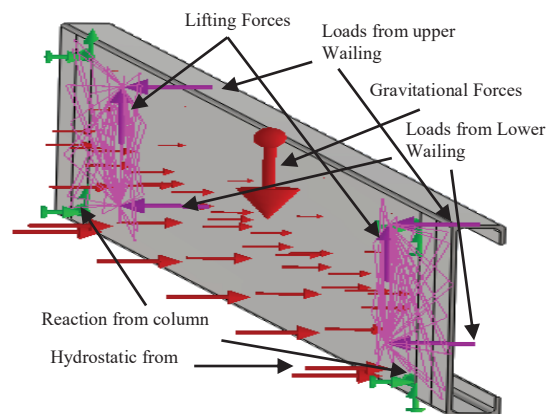


Figure 20 - Slip Form Shutters Subjected to Complex Combine Forces

The shutters fabricated by 3 mm thick mild steel sheets folded at the two ends by 90° to fasten wails and the vibrator compaction unit. The stress and strain variations of the mild steel shutter are given in Figures 21 and 22 respectively.

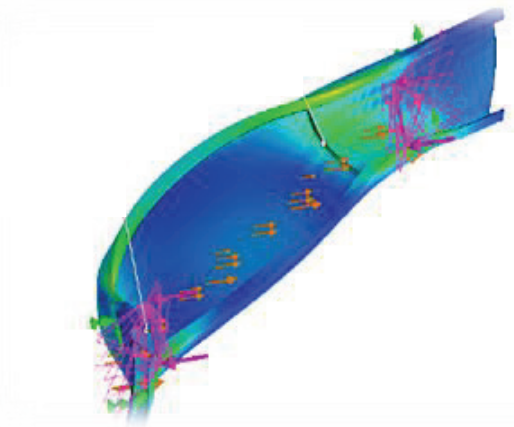


Figure 21 - Stresses Formation of the Form shutters.

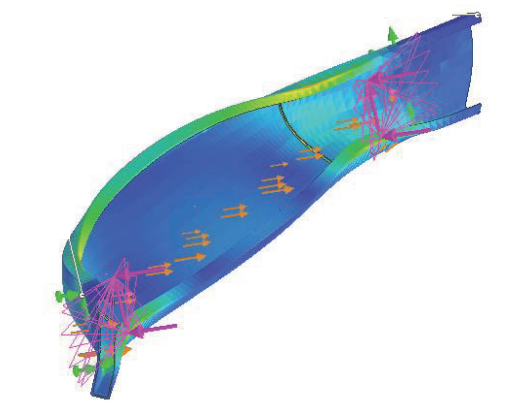


Figure 22 - Strain Variation throughout the Shutter Material

The shutter deformation between two columns due to combine forces was identified as a major problem in slip form wall construction. Figure 23 shows the deflection pattern of one side form shutter.

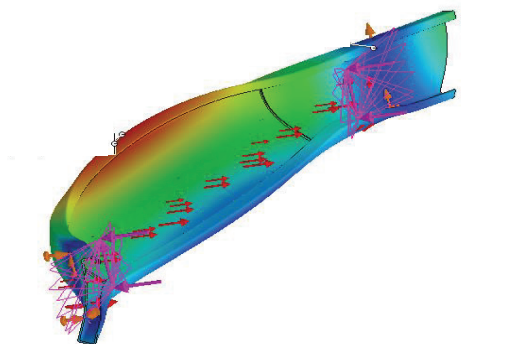


Figure 23 - Total Deflection Pattern of the Slip Form Shutter Assembly

According to the software based simulation results, the maximum deflection was obtained as 4.48 mm. However, in practice, it was observed to be 10 mm to 12 mm deformation at the mid span of the both shutters. The initial

shutter deformation, undefined complex stresses formation due to clamping, higher degree of vibration and misalignment of columns, are the main reasons for the difference between the practical values and simulation results.

11. Conclusions

Researchers always look for economical, time saving construction practices which could replace conventional approaches. The vertical continuous masonry wall construction is cost effective, material saving and allows rapid construction. Hence, it points in the right direction to achieve those targets.

According to the test results, average wall strength obtained, i.e. 4.9 N/mm², is typically good strength for masonry wall at 1:10 cement, quarry dust ratio. Hence cement to aggregate ratio 1:12 can be increased to maintain standard required wall strengths. The surface finish of a constructed wall is better than the finish from a conventional slip form wall construction. Hence plastering is not required to finish the constructed walls.

The wall construction cost of quarry dust masonry slip form found to be one third of that of conventional masonry wall construction cost. The system also attempts to construct soil compressed slip form walls for building construction.

The slip form quarry dust masonry mix is homogeneous in its compositions as against brick masonry. In relation to even vibratory compaction, compressive performance it is found that slip form are far greater than conventional brick masonry and therefore it is used as load bearing walls. In the structural performance point of view, slip form masonry construction has eliminated such weakness. Therefore, it is expected to perform even better under flexural loading.

A tactile controlled hydraulically operated mechanised slip form system is developed to construct slip form continuous masonry vertical wall panels. Greater initial setting time and heavy weight are the main drawbacks that were identified while operating the system with three operators. Quality of quarry dust cement mixing is directly affected to the strength and finishing of the wall. To obtain better performance recommended power mixing machine except manually mixing of quarry

dust and cement. It is likely that four operators are required to achieve a better performance from the system. The mechanized system was designed as bulk for heavy operational (two-tone) lifting forces. According to the test results, further developments are required to simplify the structure of the mechanized slip form system.

References

1. Manike, J. M. N. U. J. and Sooriyaarachchi, H. P. (2009), "Constructability and Performance of Continuous Masonry Wall Panels" *ENGINEER* - Vol. XXXX11, No. 04, pp. [38-45], The Institution of Engineers, Sri Lanka.
2. Kulasinghe A. N. S. (2000), "*Kulasinghe Technology for the Low Cost Housing*". National Engineering Research & Development Centre, Colombo.
3. Camellerie, J. F. (1959), "*Slip-Form Details and Techniques*," Journal of the American Concrete Institute, Vol. 30, No. 10, April 1959.
4. Dissanayake, T. A, Dissanayake U. I. and Ranaweera M. P.(2001), "*Material Properties of Slip-Form Load Bearing Wall Panel for Low Cost Medium Rise Buildings*", Fifty seventh Annual Sessions of Sri Lanka Association for the Advancement of Science, Colombo.
5. Mendis, D. L. O. (2001), "*Innovation and Self-Reliance*" Kulasinghe Felicitation Volume, Institution of Engineers, Sri Lanka, Colombo.
6. Batterham, R. G. (1980), "*Slipform Concrete*" Construction Press Ltd., Lancaster, England, and Longman Inc., New York.
7. Appuhamy, J. M. R. S., Chandrasekara, H. K. C. P., Ruhunage J. C., Dissanayake T. A. and Dissanayake U. I. (2003), "*Strength Variation of Slip Formed Load with Partial Replacement of Crusher Dust by River Sand*", Fifty Ninth Annual Sessions of Sri Lanka Association for the Advancement of Science.
8. Fossa, K. T. (2001), "*Slip forming of Vertical Concrete Structures, Friction between Concrete and Slip form Panel*". *Dr.Ing Thesis*, Department of Structural Engineering. The Norwegian University of Science and Technology, Norway.
9. Camellerie, J. F. (1978), "Vertical Slip forming as a Construction Tool", *Concrete Construction*, May 1978.
10. Perkins, A. C.(1977). "*Slip form Concrete Construction*" Fegles-Power Service Corp. Booklet
11. Camellerie, J. F. (1959), "Slip-Form Details and Techniques", Journal of the American Concrete Institute, Vol. 30, No. 10, April 1959, p. 1131.
12. Kulatilake, M. P. M. (2002), "*A Study on the Characteristics of Cement Block Manufacturing in Sri Lanka*, MSc Thesis, University of Peradeniya.