

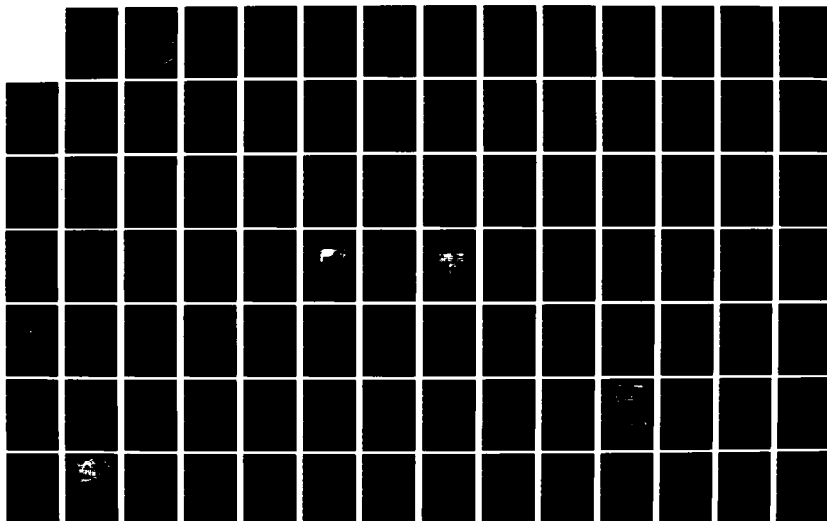
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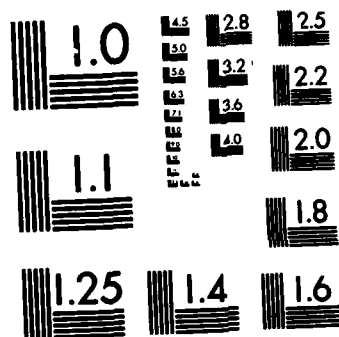
CONCRETE CONSTRUCTION USING SLIPFORM TECHNIQUES(U)
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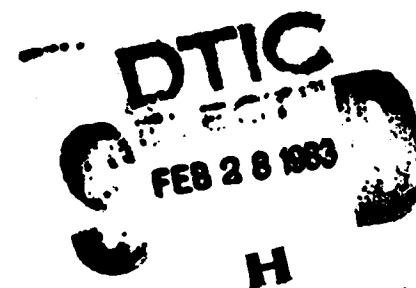
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CONCRETE CONSTRUCTION USING SLIPFORM TECHNIQUES

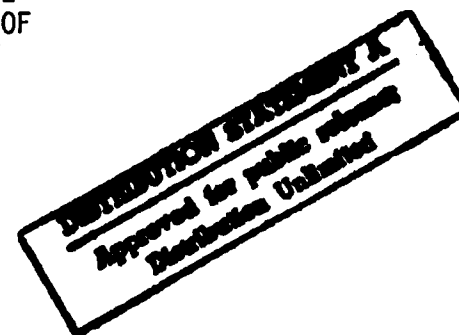
BY

BRUCE R. CARTER

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A REPORT PRESENTED TO THE GRADUATE
COMMITTEE OF THE DEPARTMENT OF CIVIL
ENGINEERING IN PARTIAL FULFILLMENT OF
THE REQUIREMENTS FOR THE DEGREE OF
MASTER OF ENGINEERING



UNIVERSITY OF FLORIDA

NOVEMBER 1982

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To my wife
Margaret
for her patience and support

ACKNOWLEDGEMENTS

The preparation of this report required the support and guidance of several individuals and organizations.

It is with sincere appreciation that I thank all the members of my graduate committee: Professor Zohar Herbsman, Professor Willard G. Shafer, and Professor Byron D. Spangler. I am especially indebted to my committee chairman, Dr. Herbsman.

I wish to thank the U.S. Navy Civil Engineer Corps without whose support this Report would have been impossible. I also wish to note my gratitude to Linden-Alimak Inc. of Bridgeport, Conn.; R. A. Hanson Company of Spokane, WA.; and GOMACO Corp. of Ida Grove, Iowa for their technical assistance.

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CHAPTER 1

INTRODUCTION

1.1 BACKGROUND

The formwork for concrete structures represents a critical part of concrete construction, in terms of cost and importance toward getting the job done properly and on time. In fact, concrete formwork frequently costs more than the concrete and reinforcing steel combined. Therefore, any system or method of concrete placement which can significantly reduce the time and/or cost of the construction project should be of great interest to all concerned.

In general, one can minimize investment in concrete formwork by:

- a. using the least number of forms required to maintain a smooth workflow of the required productivity.
- b. maximizing the reuse of forms.
- c. minimizing form size to reduce handling costs.
- d. minimizing form setup/dismantling costs.

The family of concrete slipforming techniques meets the above criteria for economy and efficiency.

This paper shall illustrate some of the basic vertical and horizontal slipforming techniques, and discuss their relative economies as compared to other concrete forming practices.

1.2 DEFINITIONS

Concrete slipform construction, which is sometimes referred to as sliding form construction, is a type of extrusion process. Plastic concrete is placed or pumped into moving forms which shape and hold the concrete until it is self-supporting. Vertical slipform techniques as the term implies, is associated with the vertical construction of such structures as water tanks, silos, and multi-storied buildings. Horizontal Slipform construction as described herein will include the techniques used in the construction of such structures as canal linings, concrete pipe, highway pavement, and tunnel inverts.

1.3 SCOPE OF REPORT

→ This report will examine the use of concrete slipforming techniques to reduce construction costs for particular structures, and discuss the basic equipment and techniques used in the slipforming process. Chapter Two will outline the history of the slipforming technique in America. Chapter Three will discuss the basic equipment and techniques employed in vertical slipforming. Chapter Four will discuss the equipment used in conjunction with horizontal slipforming techniques. Chapter Five will examine the economic and productive aspects involved with slipforming. Chapter Six is a summary of conclusions and recommendations.

It is the purpose of this report to acquaint the reader with the advantages and disadvantages of employing slipforming techniques, and to broaden the readers scope of knowledge with respect to the versatility of concrete as a construction material. ←

CHAPTER TWO

BRIEF HISTORY OF THE USE OF SLIPFORMING IN AMERICA

2.1 HISTORY OF VERTICAL SLIPFORMING

The origin of concrete slipforming is quite obscure, although it is generally accepted that the first use of this technique took place in 1885¹ when a Texan named Carrico used it to build a small concrete raft. No further development apparently took place until 1899² when the Peavey Elevator Company at St. Louis Park, Minnesota performed vertical concrete slipforming on an experimental basis. In general, slipforming was the outgrowth of continued experimentation by contractors to construct multiple reinforced concrete walls of uniform thickness, quickly and economically. Various methods of moving and lifting sectional forms were tried, but all had the same defect of leaving numerous horizontal and vertical joints in the walls.³

The method used by Peavey in 1899, employed a system of steel angle walers 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 the top of previously hardened concrete. Figure 1 provides a sketch of the Peavey system. The first true slipform 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.

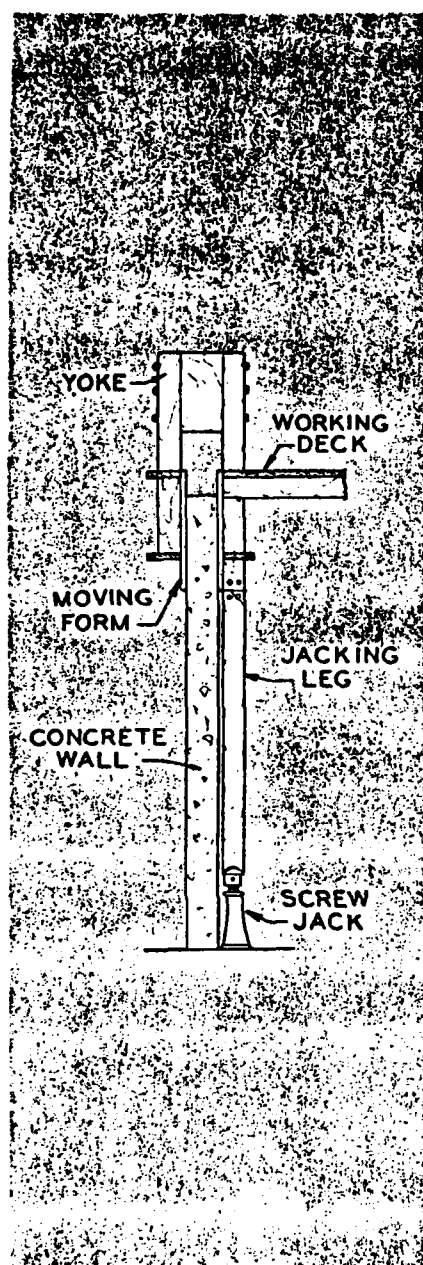


Figure 2 - Slipform Technique
Circa 1903

(Source: Linden-Alimak Inc.
Publication)

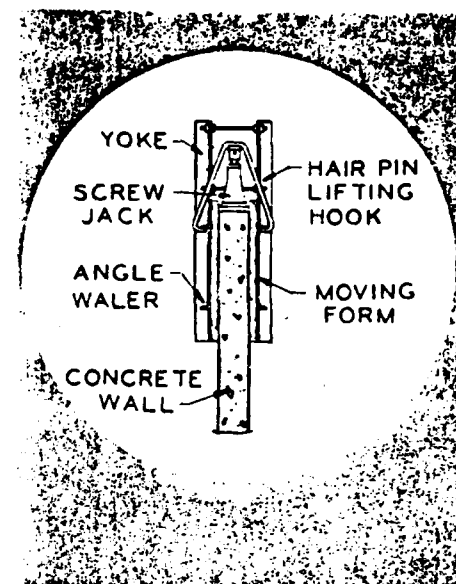


Figure 1 - Slipform Technique
Circa 1899

(Source: Linden-Alimak Inc.
Publication)

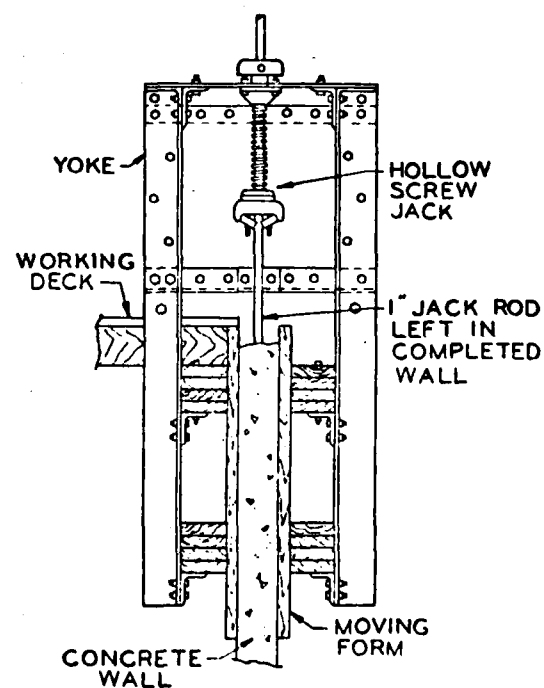


Figure 3 - Slipform Technique
Circa 1910

(Source: Linden-Alimak Publication)

This first true slipform system highlighted the problems associated with concrete vibration, fallouts, honeycombing, and wall damage by buckling climbing-tubes which had to be overcome in order to successfully employ the vertical slipform concept. 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 hollow pipe that was subsequently left in place in the completed concrete wall. Figure 3 illustrates such a system. By 1920, Fegles-Power Service (then known as Fegles Construction Company) was using a system of worm gears and rope drives attached to a central line shaft to power the hollow screw jacks. In the early 1920's Fegles-Power Service developed and used a pneumatic lifting jack, utilizing compressed air distributed from a central air compressor.⁴ Further progress was noted in the early 1940's when a Swedish manufacturer developed the now-standard hydraulic equipment which has since enabled contractors to produce record lifts. By 1958 average vertical slide rates of 6-12 inches per hour were common and use of the vertical slipforming technique was no longer being restricted to bins and silos, but was being used to construct apartment houses, water tanks, bridge piers, dam structures and even church steeples.⁶

Slipformed walls at this time were stepped rather than tapered, and the fresh high slump (5-6 inch) concrete at the top of the forms was spaded. It was thought that mechanical vibration increased the pressure on the forms, and posed some danger to the concrete within the forms that had already set.⁷

However, rapid improvements in the vertical slipform technique in the late 1950's and early 1960's soon led to average slide rates

of approximately 12 inches per hour and the use of 3-4 inch slump concrete combined with mechanical vibration. The use of lower slump concrete was made possible through the use of immersion type vibrators, concrete admixtures and air entrainment. At this time, peak slide rates in excess of 18 inches per hour were being achieved.⁸

In the last 10 years, refinements in material, equipment, and management techniques have led to slide rates of over 40 inches per hour, and application of the slip forming process to an increasing number of structural types, including tapered chimneys, communications towers, cooling towers, offshore drilling platforms, ski jump towers, nuclear shield walls, high-rise building cores, and the worlds largest dry dock.

2.2 HISTORY OF HORIZONTAL SLIPFORMING

The first widespread use of horizontal slipforming techniques involved the concrete paving of highways. The first concrete paving project in America was an experimental project completed in Iowa in November 1947, when the Iowa Highway Commission extruded a finished slab of concrete 18 inches wide and 3 inches thick without the use of side forms. In February 1948, using an improved model, the same engineers placed a 36 inch wide slab, 6 inches thick. In 1949 a slightly modified and further enlarged slipform paver placed a 0.5 mile section of county road consisting of pavement 10 feet wide and 6 inches thick.⁹

The first slipform paver was the Johnson Machine which consisted of a simple skid-mounted box equipped with a vibrator and extrusion plate. This machine was pulled by the ready-mix trucks or transit

trucks which supplied the concrete. The first production slipform paver and Quad City machine, was placed on the market in 1955. The Quad City machine was self-propelled on crawler tracks, pulled several lengths of trailing form, and was able to pave a full width, two-lane pavement. As the use of the slipform paver spread, still newer machines with more automation appeared. In 1959, the Guntert-Zimmerman Company produced a machine with electronic controls for surface elevation. This machine was available in sizes to pave as many as 3 lanes (36 feet) in one pass. At about the same time Hurst Lewis of California developed a paver, with four short crawler tracks rather than the two long tracks of other machines. The four crawlers were interchangeable with bogy wheels which permitted the paver to operate on forms as a combination spreader-finisher. In 1963 the Lewis Slipform paver in concert with a twin turbine central mix plant was able to exceed one mile of paving per day in New Mexico. A model manufactured by Koehring as early as 1963 used automatic controls for both elevation and slope.¹⁰

In the late 1950's and early 1960's slipform paving was adapted to the lining of canals. The R.A. Hanson Company which had developed a self-leveling mechanism for wheat combines in the state of Washington, was asked by construction firms in that state who were engaged in canal work to adapt their leveling device to canal machinery. The R.A. Hanson Co. canal trimmer and concrete placer proved to be very popular. In 1964, the R.A. Hanson Co. successfully designed, manufactured and used a continuous concrete cast-in-place pipe system.¹¹ Several companies during this time period also produced automatic machines for placing curbs, and sidewalks. By the late 1970's several companies were producing slipform equipment that could produce concrete barriers, parapets, and overlays.

CHAPTER 3

BASICS OF THE VERTICAL SLIPFORMING TECHNIQUE

3.1 VERTICAL SLIPFORM TECHNIQUE OVERVIEW

In general, vertical slipform construction is the uninterrupted vertical molding of concrete walls through the use of a 4-6 feet form which is lifted in small (1-3 inch) but continual increments while fresh concrete and reinforcing steel are placed in the top of the open form. Thus vertical slipforming is an extrusion process where the material is stationary and the form moves upward. Normally the setting time of concrete is 2-3 hours. Using this typical setting time and with slipforms 4 feet deep, a possible form speed of 16-24 inches per hour can be achieved. The actual median form speed however, depends on such factors as the concreting temperatures, the concrete admixtures used, the grind of the cement, the water-cement ratio, the percent of fines in the concrete aggregate, the symmetry of the structure being constructed, required variations in wall thickness, the amount and complexity of rebar placement, the jack spacing, the number of blockouts required, and the depth of the forms.

Because slipforming is an extrusion process, nothing can be cast that is not within the confines of the inner and outer sheathing of the moving forms. This means that beams, slabs, corbels, or other horizontal elements cannot be cast simultaneously with the walls, but must be placed later.

Inserts that do not project outside the formed wall are used to provide attachments for floor members and beam-and-girder frames. Inserts can include keys, pockets, weld boxes, and electrical conduit runs. Blockouts provide for such items as door frames and window frames.¹² (blockouts are discussed in more detail in Section 3.2.10.)

It is also possible to stop the slide at any time and produce conventional fixed form construction joints.¹³

3.2 THE DESIGN AND CONSTRUCTION OF VERTICAL SLIPFORMS

Vertical slip-forms are composed of three basic sections: yokes, wales, and sheathing. (See Figures 4 and 5).

3.2.1 Yokes

Yokes provide two primary functions: to keep the forms from spreading, and to transfer the load of the forms and working decks to the jack.¹⁴

The yokes are inverted U's consisting of two legs and a cross beam. The legs are attached to the wales 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 center by the jack and subject to the moments from both the vertical and lateral leg loads. Although yokes are normally of steel, they can be constructed of wood or other material.¹⁵ They should also be designed with enough clearance above the forms to allow horizontal reinforcement steel and embedded items (blockouts, insert material) to be installed in a correct fashion prior to being submerged in the concrete.

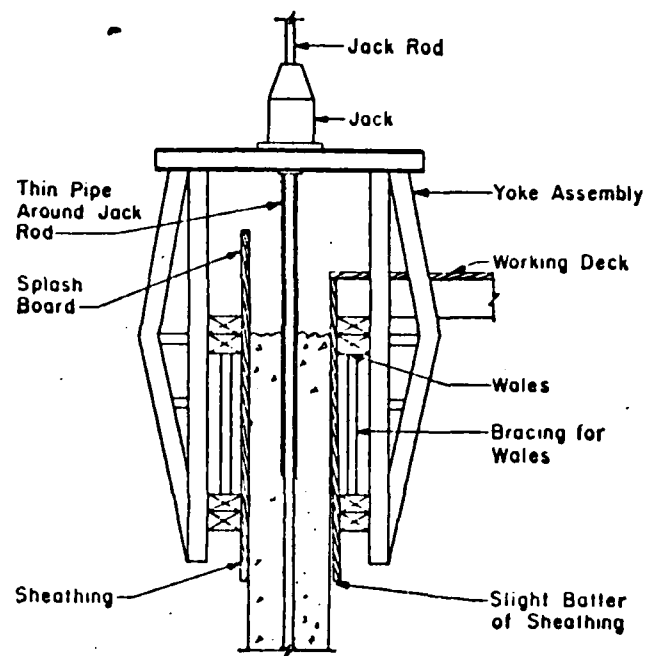


Figure 4 - Cross Section of Typical Slipform

(Source: Hurd, Formwork for Concrete
American Concrete Institute, 1973,
p. 284)

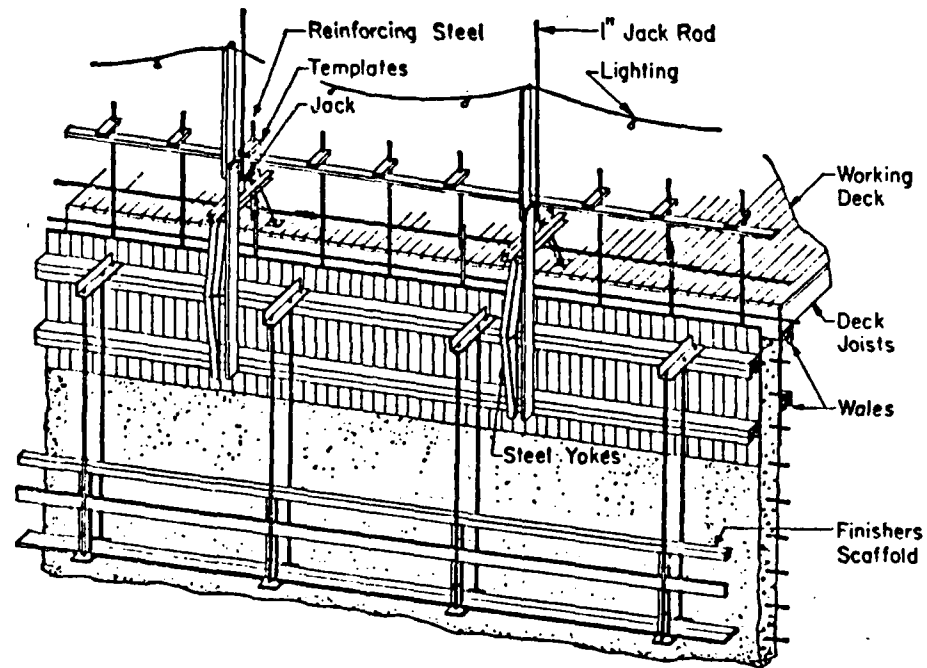


Figure 5 - Typical slip form with deck and finishing scaffold supported on wales. Templates for positioning reinforcing bars are indicated.

(Source: Hurd, Formwork for Concrete, American Concrete Institute, 1913, p. 283)

Bracing frames called false yokes are sometimes placed between yokes to support the forms at wall intersections or whenever the wales need additional support. Hence false yokes transmit their load to the wales, and do not transmit their vertical load to the jacks.¹⁶

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. In conventional slip-forming systems employing 3 or 6 ton capacity jacks, the spacing is about 7 feet.¹⁷

3.2.2 Wales

Wales serve the following purposes:

- a. They support and hold the sheathing in position
- b. They support the working platform
- c. They support the suspended scaffolding
- d. They transmit the lifting forces from the yokes to the form system.¹⁸

Wood wales are usually built up of 2 or 3 plies of two inch thick material. Two ply wales are always built of 2 inch thick material. (for example a double layer of 2x6's) Three ply wales may be a combination of 2 inch and 1 inch material.¹⁹ For structures with plane surfaces, such as buildings and piers, the wales may be 4 x 6 inch or 4 x 8 inch lumber in solid pieces. However, for structures having curved surfaces, such as silos, the wales usually are assemblies of two or three 2 x 6 inch or 2 x 8 inch planks sawed to required curvatures.²⁰ Steel wales are also used. The minimum depth of segmented wales for curved walls should be 4½ inches at the center after cutting to the required shape.²¹

3.2.3 Sheathing

The sheathing makes up the sides or walls of the forms and is the portion of the formwork which actually contains and shapes the concrete.

Since slip-forms are subjected to the hydrostatic pressure of the plastic concrete, the sheathing must support this lateral pressure with beam action between the wales, and as a cantilever at the bottom of the form. At one time the wood most commonly used for sheathing was 1 inch thick staves in 4 inch widths, tongue and groove or squared ended depending upon the job.²² The 1 inch thick staves were placed vertically to reduce drag, and often presoaked to reduce swelling during the sliding operation.²³ However, the use of staves as slip-form sheathing is diminishing and according to some experts, should be avoided.²⁴ To accommodate expansion due to moisture pickup, the staves must be spaced approximately 3/32 inch face to face (depending on the stave width and initial moisture content). Consequently, stave sheathing cannot provide a stiff partition, and a complex water system must be used to prevent the sheathing from undergoing excessive distortion. An additional, and more serious problem with staves is their tendency to deflect between the walers under the hydrostatic pressure of the concrete. This causes a negative batter, or pinching action to take place just above the bottom waler, and produces a tendency for the sheathing to pick up the concrete.²⁵ Often this results in large through-wall horizontal cracks and voids. Cracks 2 feet high and 10 feet long have been observed. For straight walls, J.M. Henry of Linden-Alimak Inc. recommends that the minimum slip-form be constructed with 3/4 inch high strength plywood braced with 2x4 inch or 2x6 inch vertical stiffeners, spaced approximately 12 inches on center. Depending on the

radius, 3/8 inch, 1/2 inch, 5/8 inch or multiple layers of 3/8 inch or 1/4 inch plywood (all with vertical stiffeners) is recommended for curved walls. If the vertical stiffeners are omitted from the plywood forms, then they too will tend to pick up the concrete and cause damage.²⁶

It should be noted that some firms still use 1 inch stave sheaths for curved surfaces, and under proper circumstances of form control, staves do have the advantage of requiring smaller wales than plywood.²⁷

All-steel forms with steel sheathing, though more expensive than wood, are economical if sufficient reuse is anticipated. 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. Steel sheathing is impermeable, but wood sheathing must be oiled or given plastic treatment in order to prevent or minimize absorption of the film of excess moisture on the inner sheath surfaces. The film of excess moisture is desirable because of its ability to reduce form drag.

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 sheathing used, but on the temperature, moisture content, workability, and rate of set of the concrete. A drag load of 100 lb. per lineal foot of sheathing is sometimes used in form design.²⁸ (The drag load is discussed in more detail in Section 3.2.4)

A slight batter of between 1/32 inch per foot and 1/16 inch per foot of the sheathing, such that the bottom of the forms are slightly further apart than at the top helps to reduce the drag of the concrete on the sheaths. In fact, the top of the forms may be slightly smaller

than the required wall thickness and the bottom of the forms slightly larger. (See Figure 4) In this way the concrete can take its final shape about halfway down the form, and is completely free of the form at the bottom. Sometimes the exterior or outside sheath is left vertical and the batter achieved by tilting the interior sheath.²⁹

There are several methods being used throughout the world to calculate design pressures acting against slipforms. The designer must take into account the effects of possible alterations in wall thickness, slide speed, initial concrete set, the condition of the formwork faces, the concrete consistency, live loads, difference in travel of lifting gear, various additional dead loads, and wind pressure.

Of particular concern in slipform design are the lateral and friction forces on the sheathing. In America, the following formula approved by the American Concrete Institute, is used to calculate the lateral pressure of fresh concrete against the slipforms:³⁰

$$P = 100 + \frac{6000R}{T}$$

where:

P = maximum lateral pressure (psf)

R = rate of concrete placement (ft/hr), ($R \leq 7$ ft/hr)

T = temperature of the concrete in the forms (°F)

In Europe three additional methods are being used to calculate the concrete pressures against the slipforms.

(a) Bohm's Method³¹

The basic assumption of this method is that pressures on the formwork are greater at lower slide rates. Calculations are therefore based on a conservative 10 cm/hr. (3.9 in/hr) and an assumed separation point between the form and the concrete

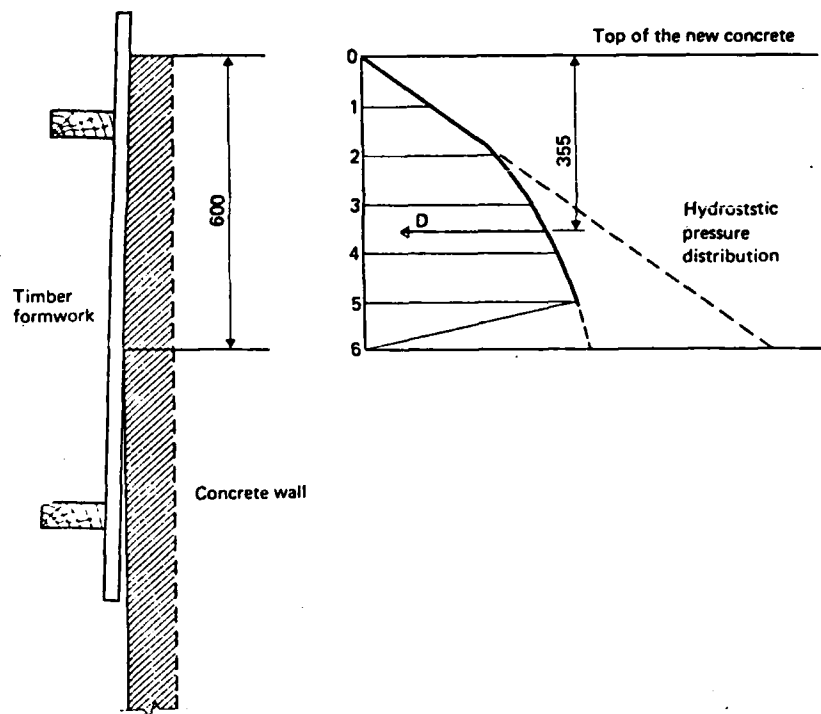


Figure 6 - Lateral Slipform Pressure Distribution According to Bohm.

(Source: Batterham, Slipform Concrete, Longmen Publishers, New York, 1981, p. 42)

a distance of 600mm (23.6 in) below the top of the fresh concrete. Figure 6 illustrates the slipform pressure distribution according to Bohm. Bohm assumes a setting time of one hour thus giving a resultant force of 280 kg per lineal meter of form. (188 lb/ft.) Bohm's Method gives a friction force of 45 kg/m (30 lb/lin. ft.) on the framework sides. For comparison the lateral pressure calculated by the ACI method under the same assumptions is 492 lb/ft. Thus Bohm's method is more liberal than the ACI method by a factor of approximately 2.6

(b) Dreschel's Method³²

Dreschel uses a combination of the earth pressure theory combined with reduced hydrostatic pressure distribution and coefficients of internal friction for fresh concrete. Figure 7 illustrates the assumed pressure distribution on the slipform using this method. For thin walls, a so-called silo pressure is assumed, while for thick walls a reduced hydrostatic distribution is used. (the reference did not define "thin" and "thick" walls) A maximum effective concrete head of 100mm (27.6 in) is assumed which produces a resultant lateral force of 485 kg/m (326 lb/ft) and a maximum reduced hydrostatic distribution pressure 1310 kg/m^2 (268 lb/ft^2). The value of the resultant is 1.7 times the calculated resultant from Bohm's Method but only 0.7 of the value obtained using the ACI method.

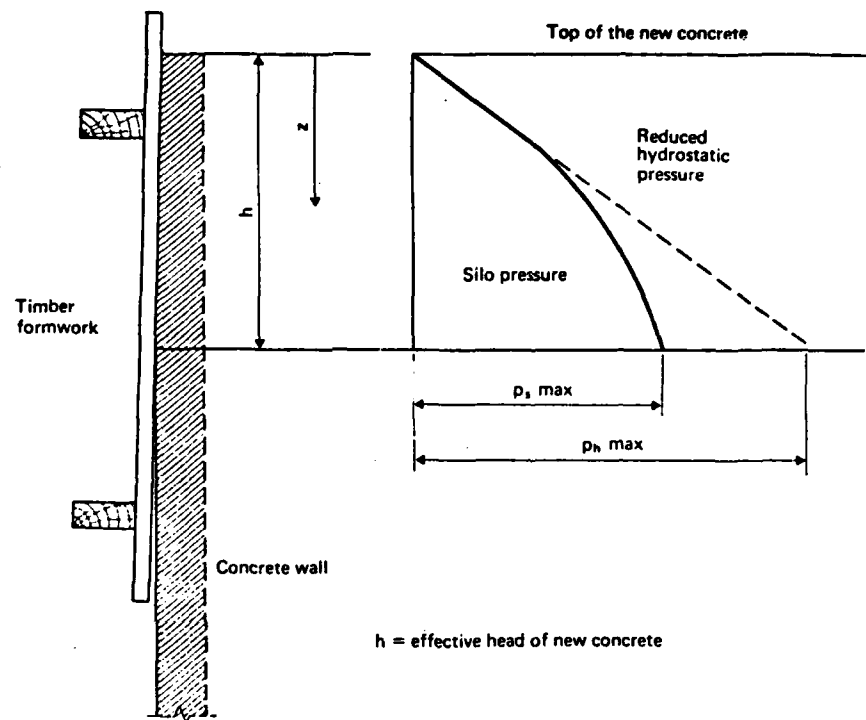


Figure 7 - Lateral Slipform Pressure Distribution
According to Drechsel

(Source: Batterham, Slipform Concrete,
Longman Publishers, 1981, p. 43)

(c) Nennig's Method³³

The third European method used is Nennig's Method. Nennig assumes a parabolic pressure distribution acting over the depth at which the concrete is against the form. Figure 8 illustrates the framework pressure distribution according to this method. For slow speeds ("slow" is not defined in the reference, but slide speeds less than 6 in/hr can be considered slow) and an effective concrete head of 1 meter, a resultant force of 375 kg/m (252 lb/ft) is calculated. Thus, Nennig's method is more liberal than Drechsels method, or the ACI method; but more conservative than Bohm's method. Nennig uses the following equation to determine the effective depth of concrete pressure against the forms:

$$h = 2a = 2v_b t_v$$

where:

t_v = setting time of concrete

v_b = sliding speed of framework

$a = 1/2h$

The resultant force per lineal meter of form width is:

$$\begin{aligned} P_n &= 2/3 (v_b t_v)^2 \\ &= \frac{4}{3} (v_b t_v) \end{aligned}$$

The lateral pressure for slip-form work is often lower than for conventional form work because vibration is less intense, the concrete is placed in shallow layers, and there is little revibration. If full internal vibration is used, the use of conventional lateral form work formulas is recommended by some experts, though this will produce a conservative design.³⁴

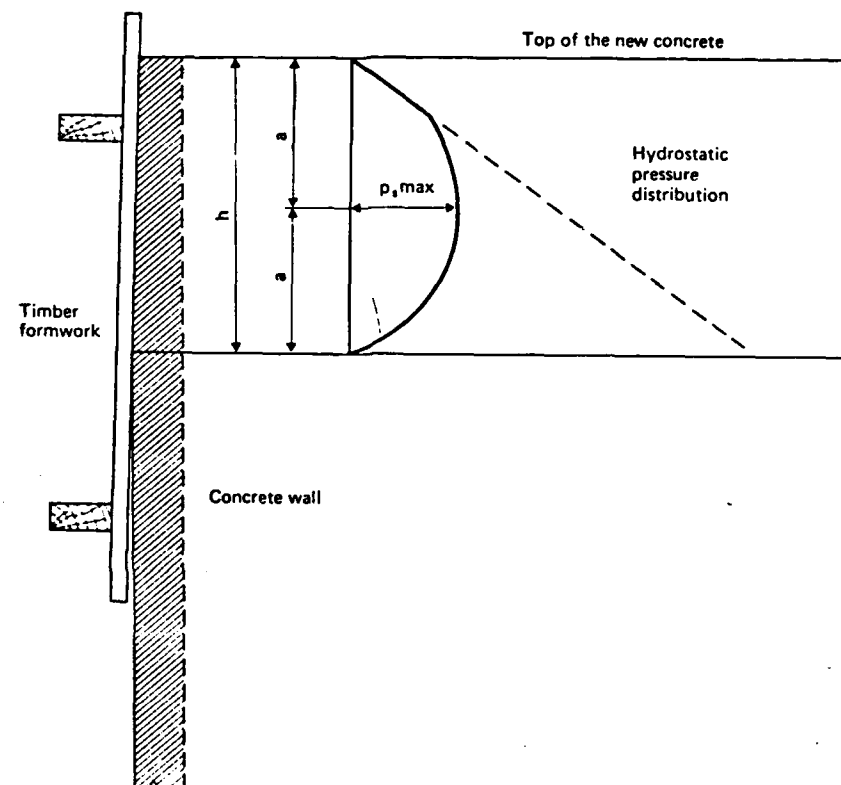


Figure 8 - Lateral Slipform Pressure Distribution
According to Nennig

(Source: Batterham, Slipform Concrete, Longman
Publishers, 1981, p. 44)

The depth of the sheathing is commonly $3\frac{1}{2}$ to $6\frac{1}{2}$ feet with 4 ft. being the usual depth.³⁵ The depth of the form depends on the desired rate of slide, and the time required for initial set of the concrete.³⁶ The lesser form depths are used when a relatively rapid set of the concrete is expected. The deeper forms have proven successful in winter weather or when greater sliding speed was desired.³⁷

3.3 CASE STUDY OF PRESSURE ACTING ON VERTICAL SLIPFORMS

3.3.1 Influence Factors

R.G. Batterham³⁸ reported on a series of tests which investigated the lateral and friction forces acting on vertical slipforms. 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, initial concrete set, type of formwork facing, concrete compaction (vibration), and concrete consistency (slump). The Group Two Factors were the uncontrollable influence factors which included wind loads, live loads, and differences in travel of the lifting gear.

The test series involved strict control and analysis of Group One factors, while Group Two Factor influence was eliminated as much as possible. Thus, climatic conditions, live loads, and the operation of the lifting gear were carefully controlled. In setting up the tests it was noted that the more rapid the rate of formwork slide, the greater the contact area between the fresh concrete and the formwork face. 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

and the degree of batter. Figure 9 illustrates these points. Batterham noted that the nature of the formwork face, especially its permeability, had a great effect on the friction and pressure factors. With timber forms, if small gaps were left between the wood slats (usually to allow for expansion), a certain amount of grout would leak through, thus reducing lateral pressure and increasing friction.

3.3.2 Test Setup

A series of three tests were conducted using a dual formwork system consisting of one timber slipform with expansion gaps between the wood slats, and a second slipform made of plywood with a watertight formwork face. Figure 10 shows the general formwork arrangement.

The reinforcement in each case was made up of 10mm diameter mild steel bars (approximately #3 rebar) spaced at 200mm (7.9 in) horizontally and vertically. The hydraulic equipment consisted of 4 sets of jacks (size not given), controlled by a central hydraulic pump.

The measurement of forces acting on the formwork was accomplished by recording strains produced on duralumin strips coupled with strain gages and 3 and 8 loop oscillographs. Figure 10 depicts the locations of the strain gages. Forces transmitted to the wales were pre-calculated, to allow for correct separation of the vertical and horizontal forces.

3.3.3 Test Procedures

Three individual tests were conducted on the dual formwork. In each of the tests, a different combination of form slide rate, wall thickness, and setting time was used. The concrete used in each case was of a plastic consistency (no slump test results given) with a

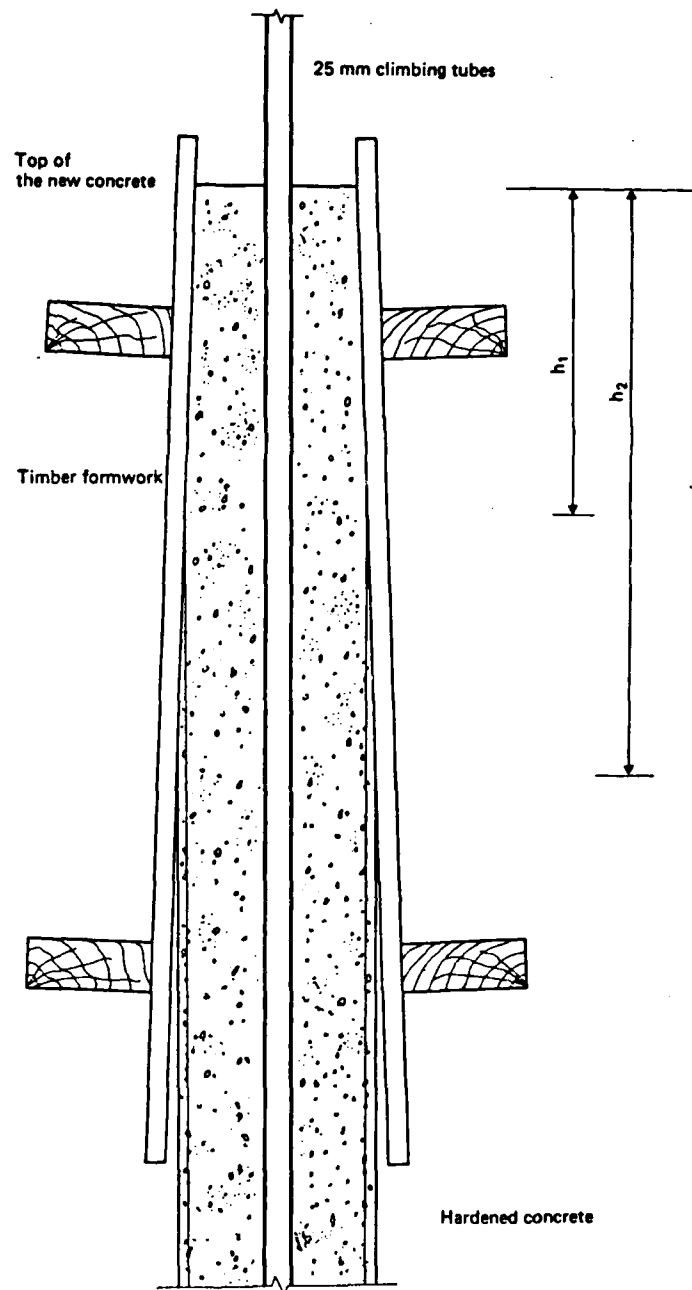


Figure 9 - Depth of Concrete Separation from the Form Varies with slide rate. At a given slide rate, the Concrete will undergo initial set by depth h_1 . At a greater slide rate, initial set won't occur until depth h_2 . Note the slight difference in wall thickness which results.

(Source: Batterham, Slipform Concrete, Longman Publishers, 1981, p. 41)

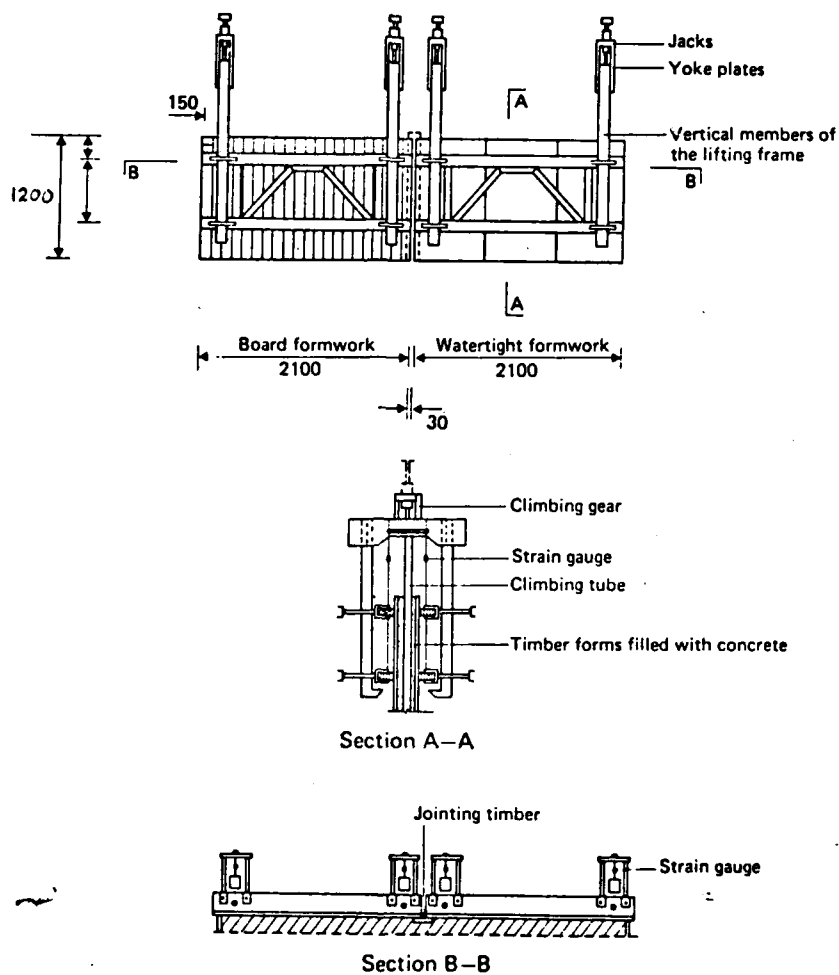


Figure 10 - Test Formwork and Strain Gage Setup

(Source: Batterham, Slipform Concrete, Longman Publishers, 1981, p. 45)

nominal 28 day strength of 375 kg/cm^2 (5334 psi). The aggregate was proportioned as follows:

<u>% Retained</u>	<u>Material</u>	<u>Particle Size (mm)</u>
18	crushed stone	15-30
22	gravel	7-15
17	sand	3-7
35	fine sand	0.2-3
8	fines	0-0.2

To begin the test, the forms were filled with concrete, and allowed to set for 3 hours before sliding operations began. Strain measurements were taken beginning with the first movement of the form, and thereafter at 200 mm (7.9 in) intervals of upward vertical form movement. After the slipform operations had begun the concrete was placed in 200 mm (7.9 in) lifts, and vibrated by internal vibration. The actual horizontal and vertical forces acting on the forms were measured concurrently with three major activities: after concrete placement, after vibration, and during formwork lifting. (The lift increment was not given, but is assumed to be on the order of 70mm (2.8 in) based on typical British practice.)

3.3.4 Test Results

The data resulting from the series of tests conducted, is given in Table 1. Figure 11 gives a generalized graph of the behavior of the forces on the slipforms once lifting took place. As graphically shown, the vertical forces on the forms are greatest just before the forms overcome surface friction and begin to move. Once the slipform is

Test		1		2		3	
Sliding speed (cm/h)		10		40		40	
Wall thickness (mm)		150		150		400	
Setting time (min)		45		15		20	
Final set (h/min)		3:50		2:55		5:5	
Laboratory temperature (°C)		19		20		14	
Formwork material		WT	BT	WT	BT	WT	BT
Friction (kg/m)	max	360	377	204	404	194	600
	mean	214	238	78	290	138	460

Pressure on the formwork (Kg/m)	Upper waling	after placing concrete	max	—	—	240	140	280	214
			mean	—	—	134	66	197	146
		after vibration	max	200	144	312	240	326	278
			mean	165	99	230	176	240	233
	Lower waling	after placing concrete	max	—	—	270	143	374	364
			mean	—	—	210	120	330	298
		after vibration	max	—	—	320	133	440	480
			mean	—	—	268	119	400	352
		during lifting	max	128	92	320	140	—	—
			mean	64	39	273	125	—	—
	resulting formwork pressure on the lifting frame		max	200	183	602	364	748	736
			mean	195	118	497	295	605	575

WT = watertight timber
BT = board formwork

Table 1 - Slipform Pressure Test Data
(Source: Batterham, Slipform Concrete, Longman Publishers, 1981, p. 46)

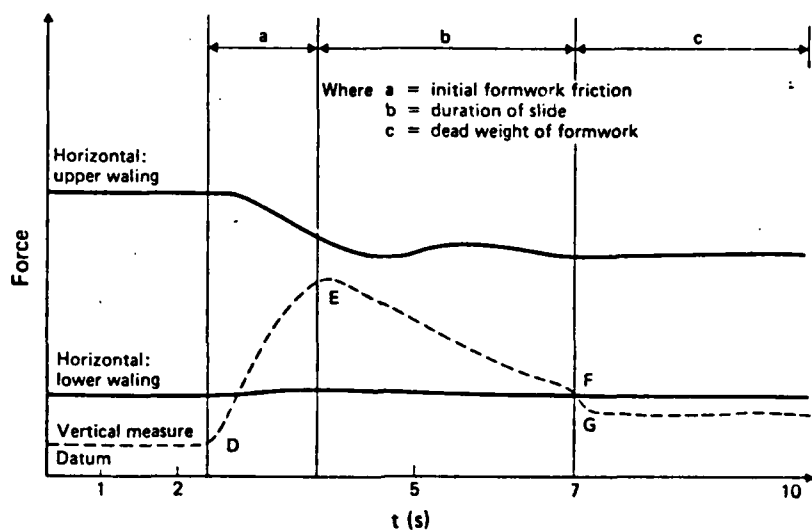


Figure 11 - Generalized Behavior of Horizontal and Vertical Forces on the Slipform During the Measuring Sequence
(Source: Batterham, Slipform Concrete, Longman Publishers, 1981, p. 48)

in motion, the vertical force continues to decrease until the hydraulic pressure in the jacks reaches zero. A 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 formwork. The horizontal force in the upper waling decreases during the slide. The initial dip in horizontal force on the upper waling is caused by the inward batter of the form which resulted from the concrete pulling on the formwork. The force on the lower waling is relatively constant, reflecting the fact that the concrete has already begun initial set by the time it reaches this lower portion of the slipform. Batterham noted that the horizontal forces increased on both wales whenever vibration of the concrete was taking place.

The extent of increase was greater with greater depth of vibration. Table 2 compares the experimental results of lateral formwork pressures with those calculated by the four methods (Bohm, Drechsel, Nennig, and ACI) previously discussed. It is apparent that the Bohm, Drechsel, and Nennig methods are inadequate. Only the ACI method gives an adequate calculated lateral pressure. In fact the ACI method gives a figure approximately 1.5 times the actual value. It must be noted however, that the ACI method does not automatically give a factor of safety. Higher slide speeds than those used in the Batterham experiment are common, and the resulting lateral pressures under extreme slide speeds (24 in/hr - 40 in/hr) will be much greater than those noted in these tests. As noted earlier, the effective head of concrete which in turn determines the lateral pressure on the formwork is influenced by the sliding speed, concrete setting time, watertightness

	Bohm (kg/m)	Drechsel (kg/m)	Nennig (kg/m)	American Regulation (kg/m)	Experimental results (kg/m)
Formwork pressure	280	458	375	1100	748 WT
Formwork friction	45	—	75	—	600 BT

WT = watertight formwork

BT = board formwork

Table 2 - Comparison of Test Results with Calculation
Methods for Determining Lateral Pressure on
Slipforms

(Source: Batterham, Slipform Concrete, Longman Publishers,
1981, p. 50)

of the form sheathing, and the depth of concrete vibrations. All of these factors except concrete vibration can be controlled. If the concrete is lightly vibrated, the concrete will achieve initial set and detach itself from the form at a higher elevation. However, well vibrated concrete is desired in many cases for the increased density and strength which is produced. Excessive vibration will have a detrimental effect on the deeper concrete which has already begun initial set. It should be noted that a watertight form tends to increase effective depth via the trapped water pressure, while simultaneously keeping the water-cement ratio higher than would occur with a less than watertight form. Batterham incorporated these facts and the test data to produce an analytical formwork model. Figure 12 shows the general Batterham model of lateral pressure distribution on vertical slipforms as a function of formwork depth. Using this figure, Batterham states that:

$$P_o = H_o + H_u$$

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

Z_o , which is the distance of P_o from the top of the new concrete is evaluated as:

$$Z_o = \frac{0.11H_o + 0.735 H_u}{H_o + H_u}$$

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 1 meter longitudinal length of slipform.

Again using Figure 12, Batterham defines three limiting values as follows:

- (a) At point A which corresponds to the top of the freshly placed concrete, which also corresponds to $j(z) = 0$, and $z = 0$
- (b) Hydrostatic pressure for the density of the concrete just placed is represented by $j(z) = pz$
- (c) Point B is the point where the concrete and form separate.

Using these assumptions, Batterham determines what he calls the first approximation of lateral pressure distribution with formwork depth. Here the lateral pressure is equivalent to a hydrostatic pressure distribution corresponding to triangle $AC_1 B_1$ and with the resultant horizontal or lateral pressure equaling P_1 . P_1 is assumed to equal P_0 . Using the given assumptions and limitations, Batterham states that:

$$Z_1 = \sqrt{\frac{2P_0}{2.25p}}$$

The derivation is not given, but the following method may have been used. Triangle $AC_1 B_1$ represents the hydrostatic pressure distribution for concrete which weighs approximately 140 lb/ft^3 or 2.25 times that of water. P equals the hydrostatic pressure due to water.

Thus:

$$\text{Force} = \frac{Z_1}{2} (2.25p)(Z_1) = P_o$$

$$P_o = \frac{(Z_1)^2}{2} (2.25p)$$

$$2P_o = Z_1^2 (2.25p)$$

$$Z_1^2 = \frac{2P_o}{2.25p}$$

$$Z_1 = \sqrt{\frac{2P_o}{2.25p}}$$

What Batterham chooses to call the second approximation is to assume that $P_2 = P_o = P_1$ and $Z_2 = Z_o$. The distance of C_2D_2 and D_2B_2 may be determined by the following relations:

$$F_1 = C_2C_1E_2 = F_2 = B_1E_2D_2B_2 = F$$

$$P_1(Z_1 - Z_o) = F_a \text{ (} F_a \text{ is not defined in the reference)}$$

where:

$$P_1 = P_o$$

$$F = F_1 = F_2 = \text{forces acting at the area centroids}$$

$$a = \text{distance between centroids of areas } F_1 \text{ and } F_2$$

Thus, lateral force trapezoid $G C C_2 D_2 B_2$ may be determined.

In what Batterham terms the third and most accurate 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 given in Figure 12.

Batterham applied the average of the 28 values of the third test of Table 1 to his lateral force models, and obtained the graphical

representation given in Figure 13 and the figures given in Table 3. The final approximation curve shows that the concrete and slipform separate at a point B_2 , 850 mm below the top of the formwork, thus indicating that the slide speed could have been increased. At the theoretical maximum slide speed, the separation point would coincide with point B.

Batterham recommends that the resulting lateral formwork pressure at point B (at the bottom of the slipform 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 series.

Therefore, for the standard British slipform 1200 mm (47.2 in) deep, and with concrete lifts of 200 mm (7.9 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 hydrostatic pressure of a point 800 mm (31.5 in) below the top of the new concrete. This lateral force distribution can be proportionately applied to all slipform 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 pressure taken at a depth equal to $2/3$ the form depth. This maximum force trapezoid represents a maximum slide rate. For less than maximum slide rates, the lateral pressure would correspond to one half the hydrostatic pressure at $2/3$ the concrete depth. It should be noted that if a slower setting concrete is used, the corresponding maximum slide speed has to be lower.

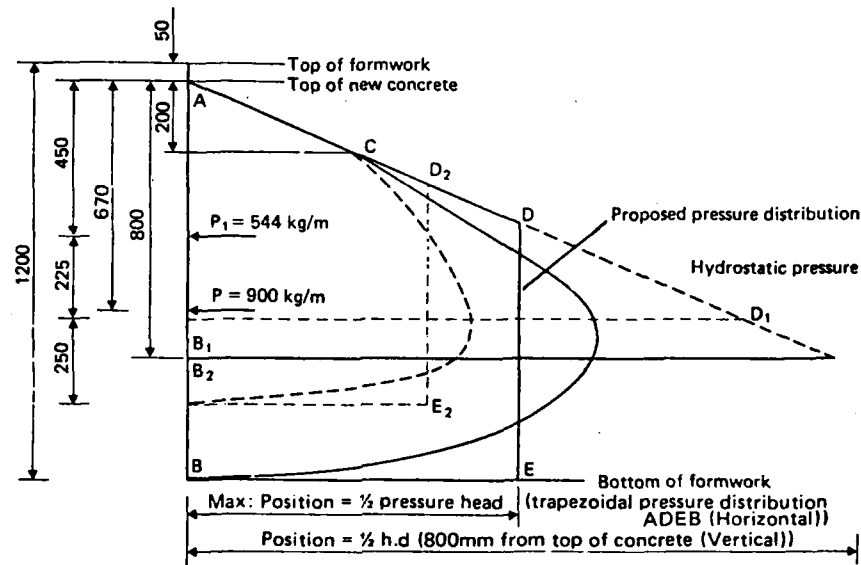


Figure 13 - Maximum Pressure on Vertical Slipform - Batterham Model

(Source: Batterham, Slipform Concrete, Longman Publishers, 1981, p. 52)

	Z_1 (mm)	P_1 (kg)	$P_1(z)$ (kg/m)
Plywood formwork	450	544	47
Board formwork	420	489	51

Table 3 - Mean Value of Readings Related to Figure 13

(Source: Batterham, Slipform Concrete, Longman Publishers, 1981, p. 50)

In concluding his analysis of these tests, Batterham states that formwork friction depends on three main factors, which in turn are all dependent on the formwork facing material. These factors are:

- a) Magnitude of effective head on the formwork
- b) Type of working face
- c) Length of time between lifts

The watertight formwork apparently creates a thin layer of grout between the concrete and the form facing, which provides a lubricating effect for the moving formwork. Tongue-and-groove formwork causes a similar lubricating layer to be formed, but to a much lesser degree. Roughness of the formwork increases with use, and this is more pronounced with tongue-and-groove formwork than the watertight plywood.

According to Batterham, the minimum wall thickness of 100-200mm (3.9-7.9 in) recommended by Dreschels Theory, was not supported by the tests. The test results gave unexpectedly high values for friction, indicating that the minimum wall size should be much larger. (how much larger, Batterham didn't state). Thus, the frictional forces can very likely be greater than the weight of the barely set concrete resulting in a tearing apart of concrete layers. Two-way reinforcing steel tends to prevent such action, and in fact transmits such forces to the hardened concrete.

Batterham also noted that horizontal cracks sometimes appear in the concrete during periods of high slide rates. He concluded that they were caused by a decrease in strength immediately adjacent to the horizontal and vertical reinforcement connections. However, such cracks closed up eventually under the weight of concrete above.

These cracks also tended to be sealed by the layer of grout between the concrete and the form face when watertight forms were used.

During the tests, a prolonged stoppage on the order of 45 minutes produced wide horizontal cracks once the formwork was restarted, especially near the horizontal reinforcing steel. Batterham noted that the degree of batter produced was dependent on 4 major factors:

- a) friction
- b) formwork pressure
- c) flexibility of the lifting frame
- d) number of connections within the lifting frame

He was basing his observations on the fact that, even if the forms were originally set at vertical, the flexing of the forms and the pressure distribution of the concrete would soon cause a form batter to be produced.

In general, as stated earlier, the slipform should be as rigid as feasible and the top of the form slightly smaller than the wall thickness required and the bottom of the form slightly larger than than required such that the desired wall thickness is at about the midpoint of the forms and the actual batter is between 1/32 and 1/16 inch per foot of form height.

Batterham concluded that the slipform tests illustrated the substantial advantages of watertight formwork over the typical tongue and groove wood plank forms. The single greatest advantage was the reduction in downward friction force by 47% when the watertight forms were used.

3.4 WORKING DECK

The working deck (See Figures 14 and 15) provides space for storage of limited amounts of materials such as rebar, and prefabricated blockouts, a platform for workers, and also lends rigidity to the formwork. A well-built rigid deck and slipform will tend to remain level.³⁹ The deck should be swept clean on a routine basis, and the storage of materials should be systematic and orderly. (See Figure 16)

The floor and joists of the work deck are usually designed for a dead load plus construction live load of 75 PSF or maximum concentrated buggy wheel load of other construction equipment loading, whichever gives the greater loading.⁴⁰ It should be noted that power buggies can give dangerously high lateral loadings to the slipform, and should be used only when truly required. Working deck beams and trusses, however, may be designed for a uniform live load of 40-50 PSF.⁴¹

Often the working deck is used as the roof slab form at the end of the slide. In such cases the working deck has to be designed to hold the additional weight of the slab.⁴²

In any case, the deflection of the working deck should not be greater than 1/8 inch or 1/360 of its span, whichever governs.⁴³

Some high capacity jack slip-form systems employ a 3 deck system. (See Figure 15) The top deck is the work platform, the middle deck becomes the forming deck, and the third level is the finishing deck.⁴⁴

In order to keep bits of hardened concrete and miscellaneous items from falling from the working deck into the forms, the decks must be scraped and swept daily. In order to insure safety for the

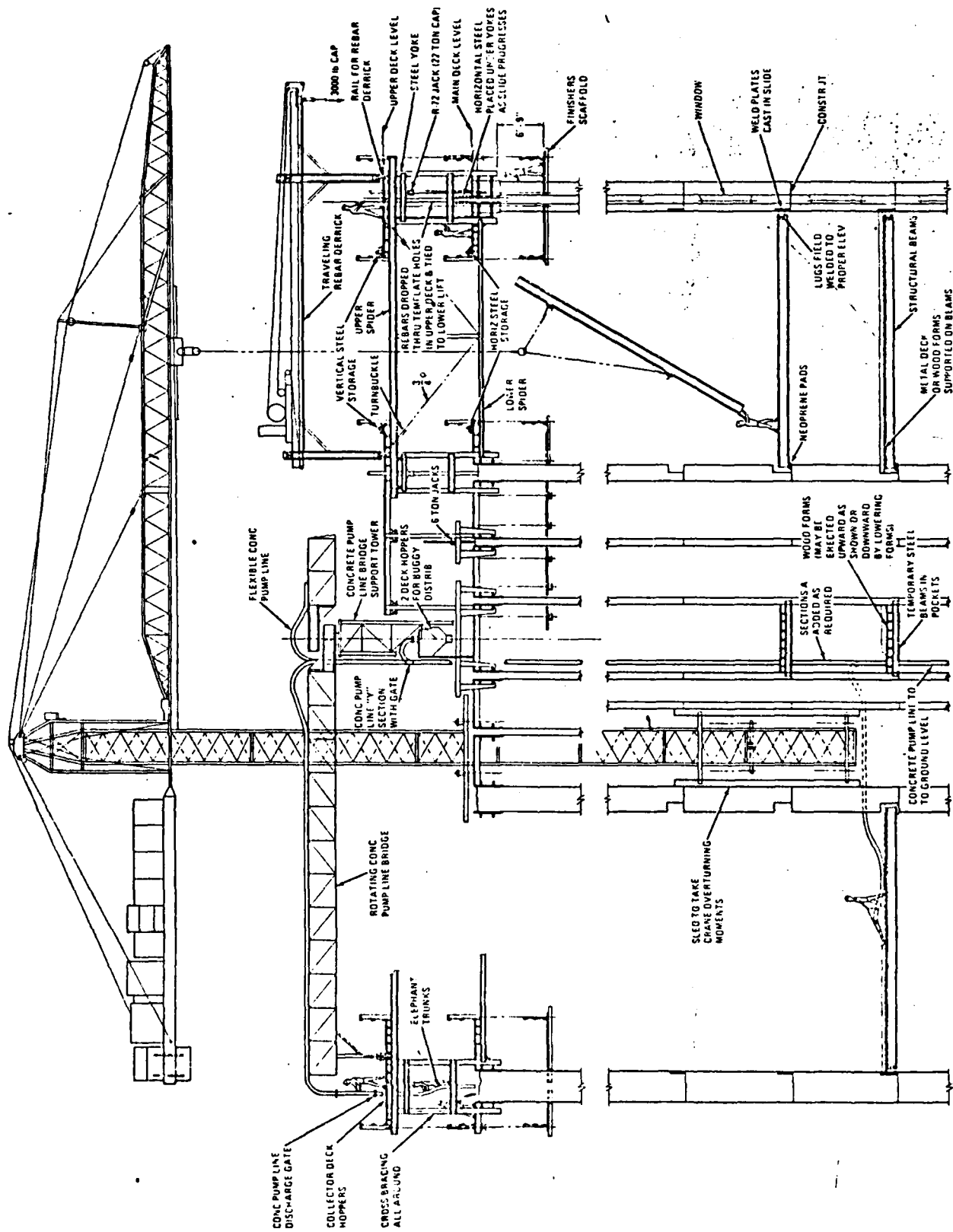


Figure 14 - Systems Illustration of High-rise Building Construction which Includes Slipforming
 (Source: Fintel, Handbook of Concrete Engineering, Van Nostrand Reinhold, New York, 1974, p. 704)

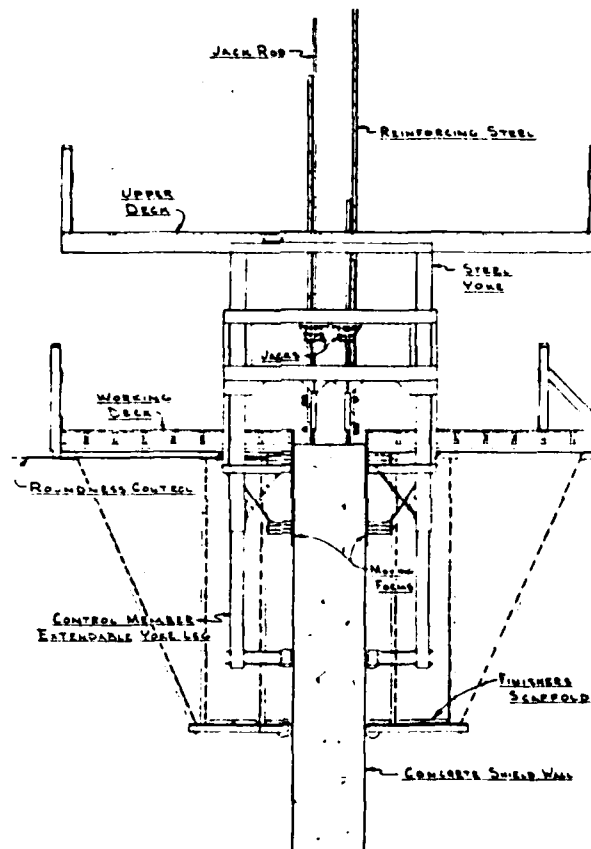


Figure 15 - Modern Slipform Assembly with 3 Deck System
 (Source: Linden-Alimake Inc. Publication)

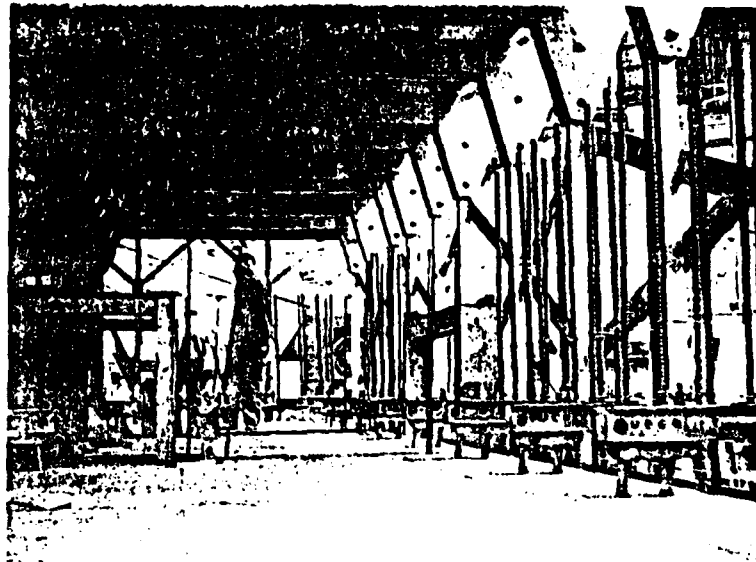


Figure 16 - View Inside Typical Slipform Working Deck
(Source: Camellerie, Vertical Slipforming as a Construction
Tool, Concrete Construction Magazine, May 1978, p. 268)

workers below the forms, it is recommended that special cleanout chutes and openings be provided.⁴⁵

3.5 FINISHERS SCAFFOLD

If the slip-forms are designed correctly and properly maintained, the concrete will emerge from the bottom of the form ready for a float and broom finish.⁴⁶ The concrete finishers are positioned on a scaffold hung about 7 feet below the forms. (See Figures 15 and 17) Equipment for application of curing compound is also carried by this scaffold. Water lines may be attached to the finishers scaffold to apply a continuous fog spray to the concrete. A shield can also be attached to the forms to protect the scaffold and fresh concrete from drying winds. (See winter concreting section of this report) In addition to the dead loads mentioned earlier, live loads of 50 lb. per lineal foot of scaffold must be supported by the slipform and jacks.⁴⁷

3.6 JACKS AND JACK RODS

Vertical movement of the slip-forms is brought about by jacks climbing on smooth steel rods about 1 inch in diameter, which are cast in the hardened concrete below. These jacks may be manual, electric, pneumatic, or hydraulic, and operate at speeds up to 40 inches/hour. Jacks typically have capacities of between 3 and 25 tons each, but much higher capacities are available.⁴⁸ The jacks carry the entire weight of the decks, scaffolds, and formwork via the yokes. (See Figure 15) In the past most slip-form systems used 3 or 6 ton jacks placed approximately 7 ft. on center.⁴⁹ However, several recent prominent slipforming projects have been performed with 22 ton capacity jacks,

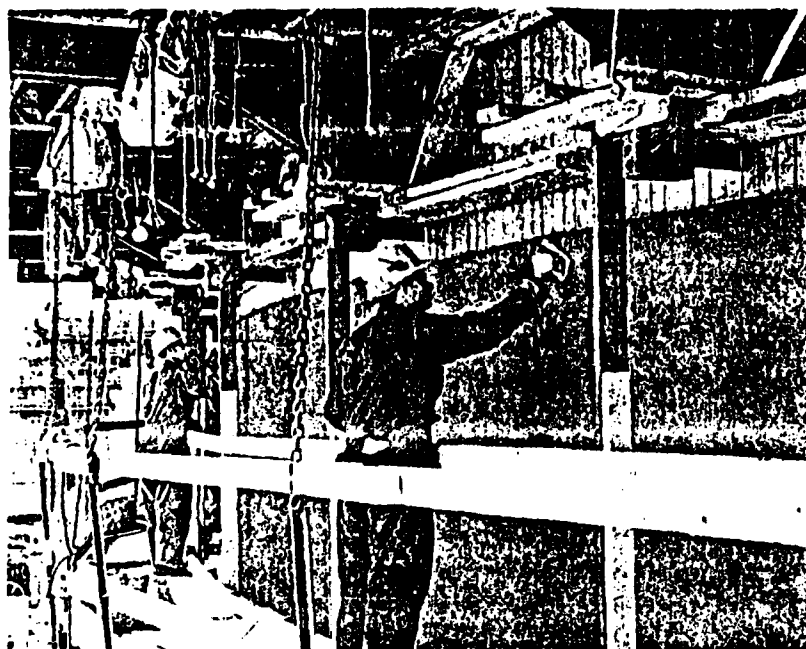


Figure 17 - Finishers Scaffold with Safety Rails
(Source: Camellerie, Vertical Slipforming as a
Construction Tool, Concrete Construction, May
1918, p. 266)

therefore requiring fewer jacks, creating more work space, and adding to project efficiency.

In any slipform system, the jacks should be placed so that they each carry nearly equal vertical loads that do not exceed the jack capacity. The steel rods on which the jacks climb should be especially designed for this purpose. If they are to be used as reinforcement, consideration must be given to splices, and the low bond value of these smooth rods. If the jacking rods are to be saved, they cannot be allowed to bond to the concrete. Bonding can be prevented by placing a thin pipe sleeve about 3 or 4 feet long around the jacking and attaching it to the yoke or jack so that it is carried upward with the forms. Since the pipe is carried upward, the jackrods are left standing in a small hole in the concrete and can easily be pulled out after the slipforming is completed.⁵⁰ The rods must be braced when not encased within the concrete, such as when there are openings or blockouts. (See Figure 18) Beyond the typical spacings, Jacks should be concentrated at corners, deck beams, concrete hoppers, bridge landing and other heavily loaded locations.⁵¹ A "heavy jack" system employing 22 ton jacks, has typically required a jack for approximately every 175 sq. ft. of core plan area on successful highrise construction projects involving slipformed cores.⁵²

Jacks are almost always connected to operate simultaneously from a central pressure or power source and climb a predetermined stroke distance (such as 1/2 inch or 1 inch) simultaneously every time the electrical or hydraulic, or pneumatic system is activated. Most jacks have excellent stroke accuracy, nonetheless, field conditions, formwork twist and load variations require a continual adjustment of form level.

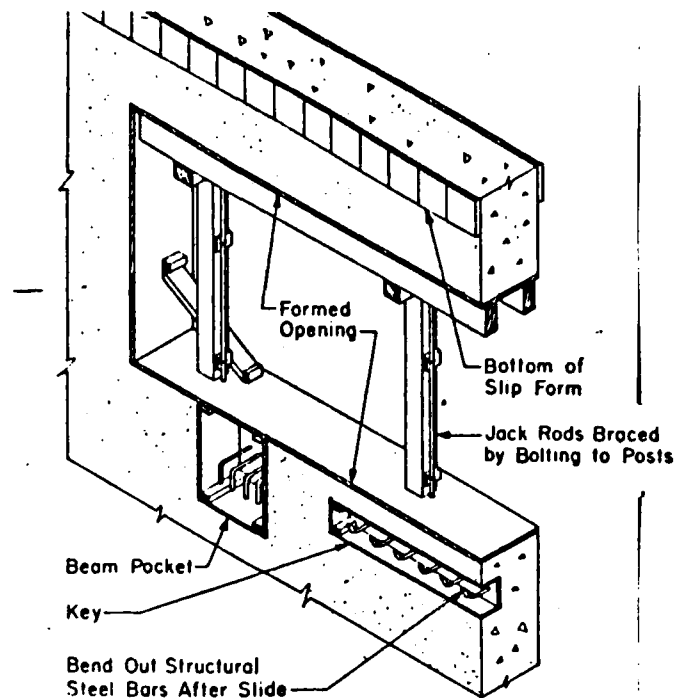


Figure 18 - Typical Forming Details to Allow for Openings, Beam Pockets, Concrete Brackets, etc. Where Jack Rods Extend Through Formed Openings, Bracing must be provided for their Support

(Source: Hurd, Formwork for Concrete, American Concrete Institute, 1973, p. 287)

Reserve jacking and placing equipment and standby service equipment, should be immediately available to the project in order to maintain a continuous operation. This is particularly important where a stop in slipforming operations would have a detrimental effect on the overall structural integrity of the project.

3.7 VERTICAL SLIPFORM CONCRETE

The basic concrete mix used in slipforming does not vary greatly from those mixes used in other construction methods. However, because of the nature of placement (6-10 in. lifts) the concrete is in various degrees of set from the top to the bottom of the form. Thus with a form moving 6-40 in/hr, the design and placement of the concrete becomes a critical item. In general, any proper mix designed for a 28 day strength of 3000 psi or higher is acceptable. Generally the slump of the concrete used in slipforming is higher than that for fixed formwork. A slump of 4 inches plus or minus 1 inch is usually specified. In hot dry climates or when using certain kinds of aggregates and cement, a higher slump than 5 inches may be required. The use of accelerators, pozzolons, "super" strength mixes, and retarders should be considered, but not for reducing the slump below 3 inches or for reducing the free water which is necessary for good form movement lubrication.⁵³

The higher concrete slump desired for slipforming results from the fact that the vibration is confined to each thin layer plus a couple of inches into the preceding layer, and a higher slump assures good bonding to the steel without heavy vibration. The higher slump also aids lubrication of the moving forms.⁵⁴

The aggregate sizes are determined by the reinforcement steel design and the wall width Ellison⁵⁵ indicates a limiting size of 1½ inches while Pruitt⁵⁶ sets ¾ inch as the maximum size. The proportion of sand should be as high as possible to produce a high degree of workability in the mix.

In addition to workability, the concrete set time, moisture content, and temperature are also key elements of proper slipform concrete control. Retarding mixtures may be required to accommodate blockouts, heavy reinforcing steel placement, inserts or other factors which might cause a reduction in the slide rate.

Minor amounts of retarding workability agents can be used to both delay the set, and increase the plasticity without adding water. However, the use of ice as part of the mixing water as a retarder is more effective and less likely to cause the complications connected with the use of special retarding agents.⁵⁷ If the slide rate is greatly reduced it may be necessary to place the concrete in layers as thin as 2-3 inches to prevent cold joints.

Because of the danger of creating uneven setting rates within various portions of the slipform, the use of high early strength concrete or accelerators can be troublesome and should be used only in special circumstances.

Rather, it is better, especially in cold weather situations, to increase the rate of set and the heat of hydration by increasing the proportion of cement in the mix.⁵⁸ Because of the importance of controlling the setting rate, Type I and Type II concrete normally should be used in slipforming.⁵⁹ In general, the concrete temperature should be in the 65-85°F range.⁶⁰

As stated earlier, the concrete is normally placed in layers of 6 to 10 inches keeping the forms as nearly full as possible and spading or vibrating each layer as it is placed. It is best that the concrete be placed alternately in clockwise and counter-clockwise directions or that other placing sequences or methods be used which prevent uneven loading and rotation of the formwork system.

Shrinkage cracks in slipform concrete tend not to be a problem because the concrete is in the form for only 3 or 4 hours, the batter of the forms allows excess water to escape, and both sides of the wall are exposed to the air simultaneously.⁶¹

The hanging scaffold or finishers' scaffold attached to the slipform allows finishers to apply a float and brush finish to the emerging concrete.⁶² Nonetheless, shingling and striation of the surface of the concrete are considered a normal part of slipforming. The shingle effect is produced by the intermittent moving of the slipform every few minutes, and striations in the surface coloring are caused by minor variations in the concrete (especially water content) and also by variations in the slide rate. Careful control of the concrete mix, concrete temperature, and slide rate will significantly reduce but not eliminate shingles, and color striations to the emerging slipformed concrete.⁶³

On some projects, the results of good management have been impressive. According to James Henry, Vice President of Linden-Alimak, the two towers of the Royal Kolani Project in Hawaii each had 38 horizontal construction joints without noticeable shingling. In fact, Mr. Henry stated⁶⁴ that detection of the construction joints required close inspection with a straightedge.

In general, when finishing the concrete surface it is desirable to chamfer all corners $1\frac{1}{2}$ inches or more.⁶⁵ This includes inside as well as outside corners. In slipforming, the use of outside acute angles is not recommended. If such angles cannot be avoided, the use of welded wire fabric should be used to give vertical reinforcement to the angle to prevent spalling.⁶⁶

It should be noted that the relative absence of joints and tie holes produces a very durable finish for withstanding the effects of climate.

Curing of the concrete is usually done by using membrane curing compounds applied by workers on the finishing scaffold. Water curing using water lines hung from the forms can be used but is subject to several problems including discoloration and erosion of the concrete. If water curing is used, it is best to use fog type nozzles.⁶⁷

3.8 REINFORCEMENT AND EMBEDMENT STEEL

The placement of reinforcing steel in vertical slipforming involves several difficulties not encountered in conventional concrete construction. The vertical reinforcement steel must be placed so as to miss the form yokes, and horizontal steel must be threaded through or tied to the vertical steel and jack rods, and be placed under the yoke beams quickly and efficiently as the forms continually move upward.

The vertical steel is held in place by templates normally placed between 4 and 10 feet above the top of the sheathing.⁶⁸ In a three deck system, the vertical steel templates are at the third deck or upper deck level. (See Figures 14 and 19) The length of individual

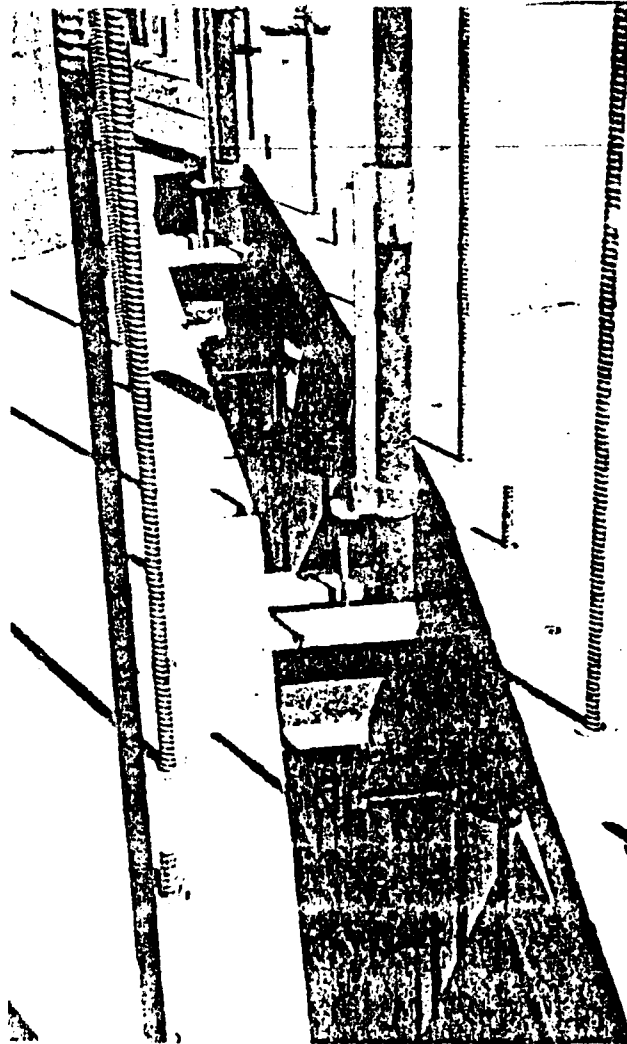


Figure 19 - Vertical Reinforcement Steel Template
(Source: Camellerie, Vertical Slipforming as a
Construction Tool, Concrete Construction, May 1978,
p. 269)

vertical steel bars are usually limited to 10-15 feet, depending on diameter, to avoid the whipping action which could occur on windy days if the rebar extended too far above the templates.⁶⁹ However, some contractors use as a rule of thumb, limiting the length of vertical rebar; to 1 floor plus lap length.

The vertical rebar splices should be staggered, not only for structural considerations, but to spread the workload for the iron workers.

With respect to the placement of horizontal reinforcement steel, some contractors prefer to weave the horizontal rebar among the vertical steel and jack rods, while other contractors using recently developed high capacity, high clearance yokes are able to efficiently tie the horizontal steel to the verticals thus maintaining better quality control.

The vertical spacing of the horizontal steel should be designed for maximum placement efficiency in the field. Camallerie⁷⁰ recommends sizing the steel for 10-12 inch spacings, except where such a design leads to bar diameters in excess of 1 inch. The lengths of the rebar are usually limited to 20 feet, since steel bars any longer than that amount would be difficult for the workers to handle.⁷¹ Pruitt⁷² recommends that the horizontal steel be placed on the outside of the vertical steel when the rebar is tied together. This would increase the efficiency and ease of placement of the horizontals.

It is necessary to detail all ties and stirrups so that they can be placed from the side. This means, of course, that stirrups be made of two or three pieces, since a single loop or closed stirrup could not be placed from the side. Ninety degree hooks are often used

in place of standard hooks, since these hooks can be placed from the side and rotated into position. Open ties must be used. Of course, special care must be taken that the design and placement of reinforcement steel does not interfere with weld plates, embedment and anchor steel, and blockouts. Pruitt⁷³ recommends the following general guidelines with respect to reinforcement and embedment steel placement during the slipforming of highrise building cores:

- (a) Dowels out of the footing to be of staggered lengths
- (b) Minimum dowel length of 4 feet plus lap length
- (c) Rebar spacing should be consistent if possible. Rebar size could be graduated.
- (d) Minimum coverage of $1\frac{1}{2}$ inch for walls, 2 inches for columns and pilasters
- (e) Vertical splices should not be made on more than $\frac{1}{3}$ of the vertical steel at any one elevation
- (f) Detail reinforcing required at weld plate locations
- (g) Consider use of weld plates in place of pockets or blockouts for beam connections. Oversize plates 3 inches and set to a plumb tolerance of $\frac{1}{4}$ inch per foot
- (h) Break out dowels and slab dowels should be 40 KSI steel, and inserts should be used in place of break out dowels when feasible
- (i) Weld plate thickness should be checked against rebar clearance.

Since the rebars are being continually engulfed by the rising concrete at the typical rate of 12-24 inches/hour, it is necessary to dictate a placement procedure which will allow orderly inspection and placement without mandating a slowdown in slide rate. The best method to insure timely inspection and placement of the rebar is to detail the horizontal reinforcement in equal horizontal layers, or at least multiples of the prominent layer spacing.⁷⁴ Such a system allows the workers to place one complete set of steel as shown on the detail drawings. The inspector can then more easily check to insure that no steel is missing.

There are several ways to check the vertical spacing of the reinforcement steel, such as providing markings on the vertical bars or embedding light angle iron templates vertically in the concrete and bolting the templates together in sections as the slide proceeds.⁷⁵

3.9 BLOCKOUTS AND POCKETS

Obviously, no projections beyond the inner face of the forms can be permitted until the forms have passed by. Packets with anchors and dowels must therefore be formed during the slipforming process through the use of inserts and blockouts. Blockouts are also necessary in order to construct openings for doors windows or utilities. Figures 18 and 20 illustrate typical forming details for pockets, blockouts and inserts.

Blockouts may also be used to reduce the thickness of the wall. The blockouts may be stationary; as in providing for a window opening, or moving; as in discontinuing a segment of wall. Pruitt⁷⁶ recommends the following guidelines for construction of blockouts:

- (a) Taper and Draft blockouts for easy removal

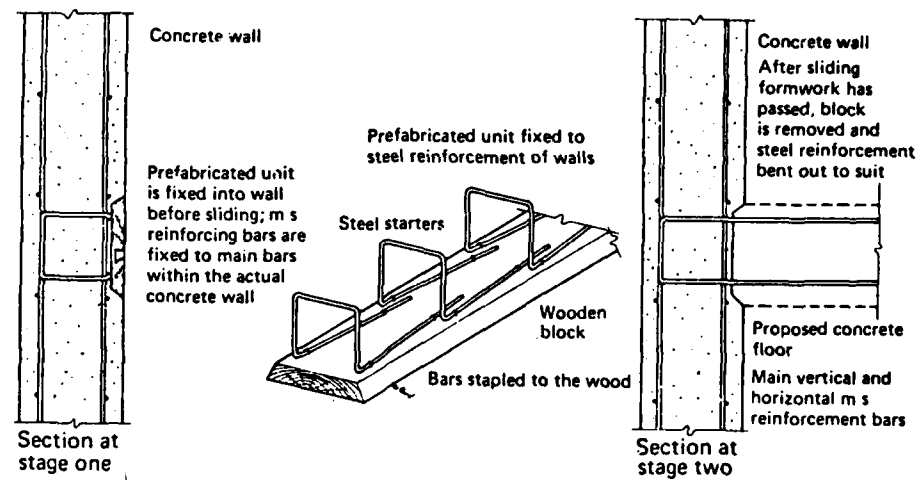


Figure 20 - Slipform Insert
 (Source: Batterham, Slipform Concrete, Longman Inc., New York, 1980, p. 81)

- (b) It is more economical to have repetition of the same blockout size, rather than varying sizes.
- (c) Reasonable elevation tolerance for blockouts is approximately $\pm 1\frac{1}{2}$ inches.
- (d) Reasonable horizontal tolerance for blockouts is approximately ± 1 inch.
- (e) Designers must note the minimum yoke spacing when considering structural alterations which will require blockouts.
- (f) Easier to work with oversized openings in which jambs will be attached to furring if possible. It is recommended that openings for mechanical/electrical fixtures and door jambs can be oversized 1 inch; and the openings for door heads be oversized 2-3 inches.
- (g) Elevator openings (as in a slipformed highrise building core), should have at least a 6-8 inch tolerance all around.
- (h) Keep openings (and thus blockouts) at least 12 inches away from wall corners. This will also keep the blockout away from the jack and yoke situated at the corner point.
- (i) Bear in mind that it is difficult to achieve a level concrete surface at the bottom of a long blockout.
- (j) Do not notch decking into door openings. Uneconomical as a blockout shape.
- (k) It is best to use sheet metal for all wall sleeves.

3.10 CONTROL OF TOLERANCES

There has been relatively little published concerning tolerances of slipforming that can be used as a technical specification. This is

probably because most slipforming is performed by contractors on a design and construct basis. Some very general guidelines may be obtained from the ACI Committee Report on, Bins Wall Design and Construction.⁷⁷ The ACI does dictate a tolerance of 1 inch per 50 feet of height.

The ACI also recommends that the maximum variation in wall thickness not exceed $\pm \frac{1}{2}$ inch for walls thicker than 8 inches.⁷⁸

During the slipforming process, several factors such as differences in form face friction, blockouts, climatic conditions, and material variances cause an imbalance of the forces on the formwork. These imbalances cause the formwork to move out of line by translation, rotation, or a combination of both. This same imbalance of forces can cause the formwork to lose its proper shape. In order to counter this ever-present imbalancing of forces, it is necessary to provide for continual adjustment of the forms. In order to maintain shape, many slipforms have a "spider" system of adjustable cables or rods holding the interior portion of the slipform together. Other slipforms are held in shape by the horizontal members and bracing of the interior working decks.

The forms must be rigid, and strong, and should be checked for level before lifting of the form begins. The level of each jack should be monitored and whenever any jack gets to be more than $\frac{3}{4}$ inch out of the proper elevation, the jack should be adjusted.⁷⁹ This can be done by bringing up lagging jacks singularly, or by causing leading jacks to skip one lift increment. Marks may be cut into vertical rebar at 1 foot spacings to serve as a general elevation check. Another method for checking elevation, involves attaching a tape measure directly between the forms and ground level, with the tape measure being unwound by the movement of the forms.

Several systems have been devised to check overall formwork level. These include water leveling systems, vertical plumbs, and optical plumb systems. With water leveling systems, there is usually a control reservoir with plastic tubing leading to various jacking points. Operators of water leveling systems must, however, be careful not to let air bubbles develop in the system, for these bubbles will cause false readings to be obtained. Camallerie⁸⁰ recommends that water level readings be taken as often as every 3 hours for structures requiring closer tolerances than normal; and that readings every 12-24 hours are sufficient to achieve the ACI tolerance of 1 inch per 50 feet of structure height. The ACI recommends that slipform alignment and plumbness be checked at least once every 24 hours, with a check every 12-18 hours being preferred.

Vertical plumbing techniques usually involve reading targets set up on the formwork at several critical points. Care is taken to place targets such that key targets are at right angles to each other. A regular transit or level is used to obtain foresights and backsights and thus determine the degree of level. Targets on the hardened concrete can be compared against targets on the forms, thus checking for rotational movement.

Optical plumbs, which are essentially a weighted free hanging telescope combined with a target at ground level, tend to be sensitive to wind and vibration, but are used at lower elevations.⁸¹

Laser beam instruments are also available. One such system involves lasers that are set up on the foundation slab and beamed to targets on the moving forms. This system simultaneously monitors slip rate, elevation, and plumbness of the jack rods.⁸²

Using good techniques and proper formwork control, tolerances within $\frac{1}{2}$ inch in 400 ft. have been consistently achieved on building cores.⁸³

However, to set such achievements as a standard is unrealistic. Pruitt⁸⁴ recommends the following tolerance goals:

- (a) Wall thickness tolerance, $-\frac{1}{4}$ to $+\frac{1}{2}$ inch.
- (b) Plan alignment along entire length, ± 1 inch.
- (c) Variation from plumb, $\pm \frac{1}{2}$ inch in any story and $\pm 1\frac{1}{2}$ inch over the entire height.
- (d) Variation in location and placement of embedded plates, ± 2 inches (both in horizontal and vertical directions).
- (e) Variation in alignment of embedded plates $\pm \frac{1}{4}$ inch in 1 foot.
- (f) Variation in size and location of sleeve, ± 2 inches.

With regard to nuclear shield wall construction, the engineer is faced with a different set of tolerance limits, and additional complicating factors influencing the structural design and construction.

Because these walls are typically 2.5 -3 feet thick, they are included in the category of mass concrete under some codes. However, as leading engineers such as J.C. Ellison of Fegles-Power Corp. have pointed out, even slipforming a wall 3 feet in diameter, really involves placing 6-10 inch layers of concrete that will be exposed to the air within 4 hours. Thus the concrete temperature standards for mass concrete are really too low to apply to typical slipformed shield walls.

Shield walls involve high reinforcing steel concentrations involving 550 lb. or more of steel per cubic yard of concrete, and greater forces

acting on the formwork than in typical slipform wall construction.⁸⁴ The need for wall placement precision is less stringent. Ellison⁸⁵ recommends the following tolerance guidelines:

- (a) Variation from plumb, ± 4 inches for total height, taken at the vertical axis of the structure; or no more than ± 1 inch in any 20 feet of wall height.
- (b) Variation from true circular section, ± 3 inches, measured along the radius from vertical axis of the structure.
- (c) Variation of wall thickness, $-\frac{1}{4}$ inch to $+1$ inch.

As in all vertical slipform construction, the formwork will always have some tendency to drift and rotate during the slipforming operation. As stated earlier, the greatest forces tending to drive a form system out of shape are those caused by the imbalance of forces associated with large blockouts. In the slipforming of large shield walls, the traditional central "spider" network of braces and cables are not enough to control drift and rotation of the forms. In some cases, an additional inner and outer supporting ring trusswork is added to maintain form shape. However, this trusswork will not prevent rotation. On one shield wall project, two 3 ton hoists were used to counteract rotational forces.⁸⁶ Lateral loads can also be added to the formwork system to counter imbalances of load caused by large blockouts.⁸⁷

Wall thickness in shield wall slipforming, as in all slipforming is controlled by the yokes. In shield wall construction however, the yokes are an integral part of the inner and outer ring trusses. In order to allow for the failure of any one jack, these ring trusses must be designed to handle the forces spanning over a single jack

support. It should also be noted that with the increasing use of 22 ton jacks vice the traditional 3 ton setups, the typical jack spacing is increasing from the former 7 feet to approximately 21 feet. This requires yokes approximately 3 times stronger in order to maintain the proper form stiffness.⁸⁸

3.11 RATE OF SLIDE

The rate of slide is essentially dependent on the condition of the concrete as it emerges from the bottom of the forms.

The importance of having a consistent concrete mix is therefore critical, and good quality control must be maintained.

The amount of time the concrete spends in the forms, and the amount of time required for the concrete to sufficiently set to the point of being self-supporting should be determined beforehand. Typically, the concrete in slipforming operations, spends about 3-4 hours in the forms, and the bearing strength of the concrete as it leaves the forms is about 300 psi.⁸⁹

The maximum slide rate is, therefore, limited by the depth of the forms and the set time of the concrete. As noted earlier the depth of the forms is typically about 4 feet, with 3½ feet being the practical minimum, and depending on the source, with 6½ - 10 feet being the maximum. Generally, forms much less than 4 feet in depth don't give the concrete sufficient set time, or provide an adequate margin for error. Forms greater than 4 feet in depth experience a dramatic increase in drag forces, although deeper forms may be required for winter concreting, or when more rapid slide rates are desired.

Although the maximum slide rate can be designed and planned for before construction operations begin, a change in concrete temperature, or the necessity to install blockouts or complicated rebar arrangements can require a change in the slide rate. For these reasons, a supervisor experienced in slipform operations must be present at all times to ensure that the most rapid slide rate feasible is being maintained.

If the slide is too fast, the concrete will be too soft at the bottom of the forms causing a "blowout". Conversely, if the slide is too slow, the forms will tend to lift the partially set concrete causing crevices and gaps within the concrete.⁹⁰

The rate of slide is usually checked by pushing steel rods into the fresh concrete to determine the depth of hardened concrete. A minimum of 12 inches and a maximum of 30 inches is recommended.⁹¹ The rate of slide can also be checked by scratching the concrete as it emerges from the forms. This technique though, requires much experience.⁹²

Figure 21 illustrates the relationship between hardened concrete depth, concrete set time, and slide rate.

Some contractors have removable sections built into the forms, so that at periods of 1, 2, and 3 hours after the initial filling, certain sections can be removed to check concrete hardness. This technique allows the contractor to start the form movement as soon as possible (thereby reducing form drag), and gives the initial maximum slide rate feasible.

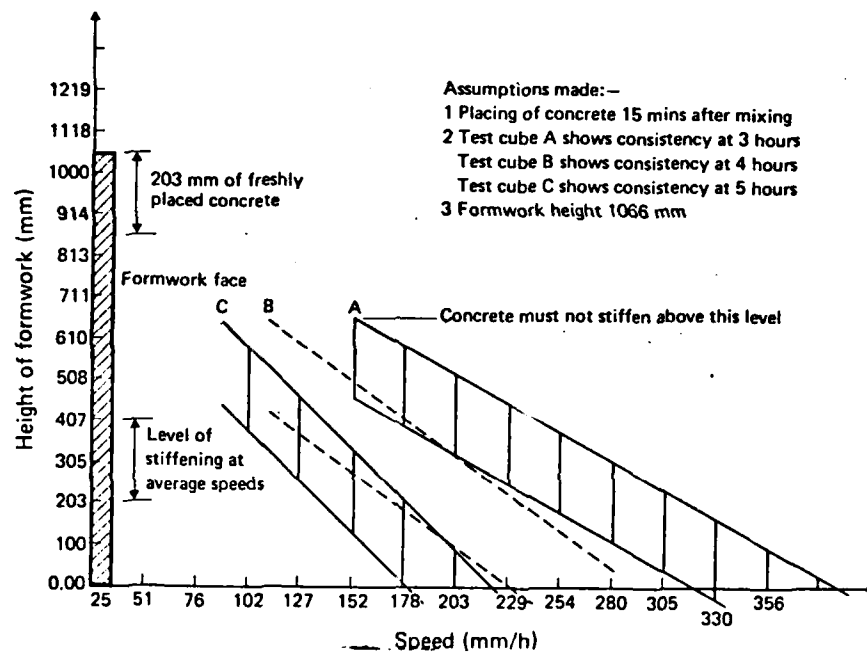


Figure 21 - Graph of the Level of Hardened Concrete Relative to Form Depth, and Set Time

(Source: Batterham, Slipform Concrete, Longman Publishers, New York, 1981, p. 29)

With forms 4 ft. deep, the rate of slide will normally be 16 to 24 inches/hour.⁹³ The average slip-forming rate for silo work is 10 to 15 inches per hour, and the average slip-forming rate for buildings is 15 to 20 inches per hour.⁹⁴ Of course, on projects with numerous delays due to placing blockouts, inserts and rebar placement, the overall slide rate will be below average.

Despite the design slide speed, hot weather may make it necessary for jacking speeds of up to 40 inches per hour to be attained.⁹⁵ Because of such variances in "maximum" slide rate, extra jacking capability above the design slide rate should be available. The alternative is the addition of retarder agents to the concrete, and additional risk of non-homogeneous concrete mix.

3.12 Distribution of Concrete

This section includes only a cursory look at concrete distribution during slipforming operations, as the methods used are many and varied, and limited only by the imagination.

In slipforming, it is required that the concrete be lifted vertically to the forms. The usual methods of doing this, include tower cranes, hoisting towers, and concrete pumps.⁹⁶ When the volume of concrete is large, the most economical method of moving the concrete to the form level appears to be through the use of a tower crane which itself is carried upward by the moving formwork system.⁹⁷ Hoisting towers or winches sitting on one of the slipform decks, and lifting concrete up through the center of the structure can also be an economical method in most cases. Pumping the concrete can be very economical, although limited by the maximum lifts and capacities of the pumps.

At the working deck level, distribution of the concrete can be accomplished with wheelbarrows, monorail systems, crane, conveyors, pump, buggies, or combinations of these methods.

Some contractors have placed concrete at two or more points on the working deck simultaneously.

On one highly successful project the contractor pumped a total of 22,000 cubic yards of concrete through a 5 inch pipe into the structure and thence up a standpipe to a mini-mixer placed at the center of the formwork spider. The mini-mixer split the concrete flow into 2 lines which were attached to 2 booms whose ends rested on rubber tired buggies. The concrete, in effect, was pumped directly to the forms through a maximum elevation of over 212 feet, thus eliminating the need for tower cranes.⁹⁸ It must be noted that when using concrete pumps, the pumping rate must be high enough to prevent plugging, thus the use of a single pump with a line split, can succeed where two separate pump lines may not.

In the case cited above, the contractor credited the improved concrete delivery system, as one of the reasons he was able to underbid the competition by a huge margin, leaving 1 million dollars on the bidding table on a 10.5 million dollar job.

In any event, the relative costs of delivery systems of the concrete to the slipforms is a significant aspect of the overall economy of the construction operation.

3.13 VERTICAL SLIPFORMING IN WINTER

Vertical slipforming in cold weather is not recommended, but slip-form operations can be successfully conducted at temperatures below

40°F. Camallerie⁹⁹ recommends that the following special provisions be considered when undertaking vertical slipform operations in cold weather:

- (a) Use of Type III cement with air entrainment.
- (b) Keep the concrete temperature at 70°F in the forms.
- (c) Use a protective enclosure to keep the air around the concrete at 70°F for at least 24 hours.
- (d) Ensure reinforcing steel is free of ice.

It is possible to use Type I or Type II cement or to maintain the air temperature at only 50°F, but these provisions necessitate a minimum curing period of 3-5 days. To illustrate the effect, assume a slide rate of 6 inches/hour and a 3 day curing period. During the curing period the forms will have moved 36 feet, thus necessitating a protective enclosure 36 feet high to shield the green concrete and maintain the required temperatures.

An enclosure 36 feet high attached to the forms, would complicate efforts to keep the forms plumb, and could even jeopardize the sliding operation. However, an enclosure 12 feet high would be manageable, reasonably safe and far more economical. A 12 feet high enclosure equates to a protection period of 24 hours, at the assumed slide rate of 6 inches/hour. And, as alluded to earlier, a 24 hour protection period is most feasible with high early strength concrete.

Canvas tarpaulins and polyethylene sheets, are probably the most common materials associated with protective enclosures, although Camallerie¹⁰⁰ prefers enclosures constructed of rigid panels of plywood, masonite, or insulation board. Rigid panels hold the air in better

since they don't flap in the wind. Hanging the enclosure in a series of sections provides safety against one detached section from pulling the other sections down with it.¹⁰¹

Steam heat is preferred since a dry heat would tend to dry out the concrete and hinder hydration.

The inside and outside of the green concrete walls should be maintained at as nearly equal a temperature as possible to minimize temperature cracks.¹⁰²

Because of the lower temperatures, the setting time of the concrete is slower, and the concrete must spend a greater period of time within the forms. For these reasons, a slower slide rate and deeper forms are used in cold weather slipforming.

The durability of the concrete is especially important for structures which will be exposed to freeze-thaw cycles. A low water/cement ratio will result in a more durable concrete. Strength in concrete is a physical phenomenon, where the hydrated cement fills capillary voids within the concrete.¹⁰³ A high water/cement ratio means that a lot of void space will be left over after the cement has hydrated. When the water to cement ratio gets to 0.70 the voids start connecting. The freezing point of a super-saturated water-cement mixture is very low, whereas the freezing point of the mixture in large pore spaces approaches the freezing point of water.¹⁰⁴ The durability of the concrete is therefore related to the water-cement ratio. Thus, the lowest slump concrete feasible for use in the slip forms will be required in cold weather areas. The protection of the concrete is critical since strength gain practically stops when moisture required for curing is no longer available.¹⁰⁵ The use of antifreeze compounds or other materials to the

concrete should not be permitted, as these materials seriously affect other concrete properties.¹⁰⁶

Assume that the desired strength of the concrete is 300 psi as it emerges from the forms, and Type IIIA cement is used. The strength of Type IIIA cement at 12 hours is 500 psi at 70°F.¹⁰⁷ Assuming a linear rate of hydration, the concrete would reach 300 psi at 7.2 hours. For slipforms 6 feet deep this translates to a maximum slide rate of 10 inches/hour. Reducing the curing temperatures from 70°F to 50°F will reduce the curing temperatures by approximately 50%¹⁰⁸, thereby reducing the maximum slide rate in the previous example to 5 inches/hour. A 300 psi strength for the emerging concrete may be very conservative, since the compressive stress at the base of the 555 ft. high Washington Monument is only 300 psi.¹⁰⁹ The fact remains that slower slip rates and additional heating costs are necessities of cold weather vertical slipforming.

3.14 FORM STRIPPING

Once the forms have reached the top of the structure and the jacking is complete, the weight of the forms is usually transferred from the jacking rods to the finished wall. This is generally done by sliding bolts through carefully placed holes in the walls just below the wales. Once the weight is off the jacks, and jackrods, the formwork, jacks and jackrods may be removed and used elsewhere.

If the working deck is to serve as the roof slab form, as is frequently done, small boxes need to be constructed around the vertical members of the yokes so they will not be keyed into the roof slab. Upon removal of the yokes, the boxes are stripped and the resulting cavities filled with concrete.¹¹⁰

The removal of the inside forms can be facilitated by leaving holes in planned positions in the roof slab to enable the hanging of a stripping scaffold.¹¹¹ The removal of the outside forms does not need to involve any special procedures.

The form stripping operations must be properly organized and controlled in order to save labor costs, and ensure reuse of formwork materials.

Although safety is of paramount importance throughout the construction sequence, there is a greater opportunity for accidents during formstripping operations, with relatively large amounts of waste materials or pieces of formwork stored high up on a structure, and the dismantling of formwork and scaffolding taking place.

So unless the stripping sequences are organized in detail, removing formwork can be both a wasteful and a dangerous exercise.

3.15 SPECIAL APPLICATIONS

Vertical slipforming has been used in a variety of innovative ways to cut the construction time or cost of several projects. A few of these special applications are described herein to give the reader a sense of the breadth of application possible with vertical slipforming.

3.15.1 Vertical Shaft Linings¹¹²

Both single wall and double wall vertical shaft linings can be slipformed. In 1979, an Indiana contractor constructed the first underground double wall slipformed concrete shaft linings in North America. The design called for an unreinforced outside wall 1 foot thick and an annular space 9 inches across, and a reinforced inner wall 2.3 feet

thick. The annular space was filled with a bituminous mixture. The outer 1 foot thick wall was built with 10' jump forms descending the shaft, while the bituminous mixture and the 2.3 feet thick inner wall were slipformed from the bottom up. Figure 22 illustrates the formwork and working platform setup. The concrete slump was 4-4.5 inches and slide rates in excess of 24 inches/hour were attained.

3.15.2 Dry Dock¹¹³

The worlds largest dry dock (able to accommodate 1 million ton ships) was constructed primarily of a series of slipformed caissons. Each caisson is 69 feet high, 102 feet long, and 56 feet wide. Since several caissons were required, they were produced in a casting yard, using slipforms hung from a large steel truss gantry. The gantry would straddle the caisson during slipforming operations. The caissons were slipformed at an average rate of 16 inches/hour, in 100°F heat and 90% relative humidity. At times the jacking speeds were increased to keep the concrete from setting in the forms, but the relative thinness of the walls (10-16 inches) kept the heat of hydration from being a problem. The project was completed 22 weeks ahead of schedule.

3.15.3 Providing a Facing for Mass Concrete¹¹⁴

A Japanese contractor used a single face slipforming system in conjunction with concrete and steel bonding facilities to triple construction speed on a hydroelectric project. The unconventional one-sided slipform required a special bearing frame to prevent it from being pushed outward by the weight of the concrete. The bearing frame was constructed of vertical 8x8 H-beams set at the back of the slipform at 6.5 feet intervals. Figure 23 gives a simplified view of the slipform

bearing system. The concrete was pumped alternately to 2 main distribution hoppers on the slipform frame. Each hopper in turn distributed the concrete to a pair of sub-hoppers, which in turn fed (again alternatively) ten 8 inch diameter discharge hoses, in order to balance the distribution of the concrete. The slipform rose in 1.6 inch increments at an overall average rate of approximately 2 inches/hour.

3.15.4 Changing Sections

The wall thickness of a slipform is usually reduced by jacking the form free of the previously placed concrete and relocating one of the form faces, or by placing an insert on one or both of the inner form facings. It is important to note that when the reduction in thickness is on one face only that the jack rods will no longer be in the center of the slipformed section, and a resulting imbalance of pull on the yokes will result, which must be balanced.¹¹⁵ There are also prefabricated circular metal slipforms being manufactured in Japan which can be made to change shape by changing the length of the inner spider arms, and through the use of overlapping sheathing which can simultaneously reduce form circumference by an alternately sliding over and under neighboring sheathing.

3.15.5 Standard Slipform Machines

Numerous standard slipform machines are available to construct such common structures as silos and chimneys. Such machines are commonly available in sizes from 6 feet to 30 feet in diameter, with provisions for reducing wall thickness during the slipform operations. These standard slipform packages which can be leased or rented, normally

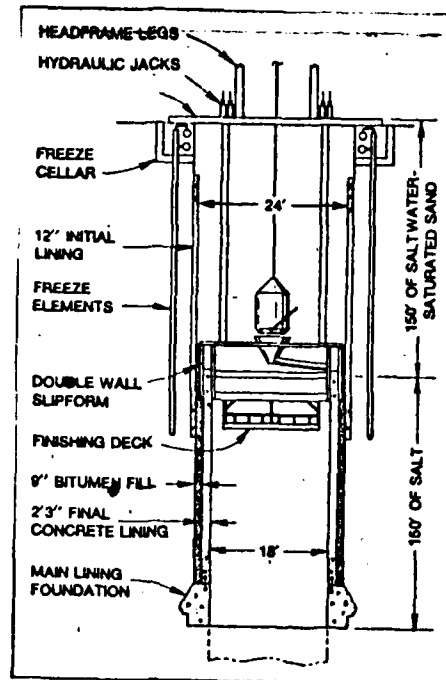


Figure 22 - Specially Constructed Slipform for Double-Wall Shaft Lining
(Source: Engineering News Record, October 11, 1979, p. 30)

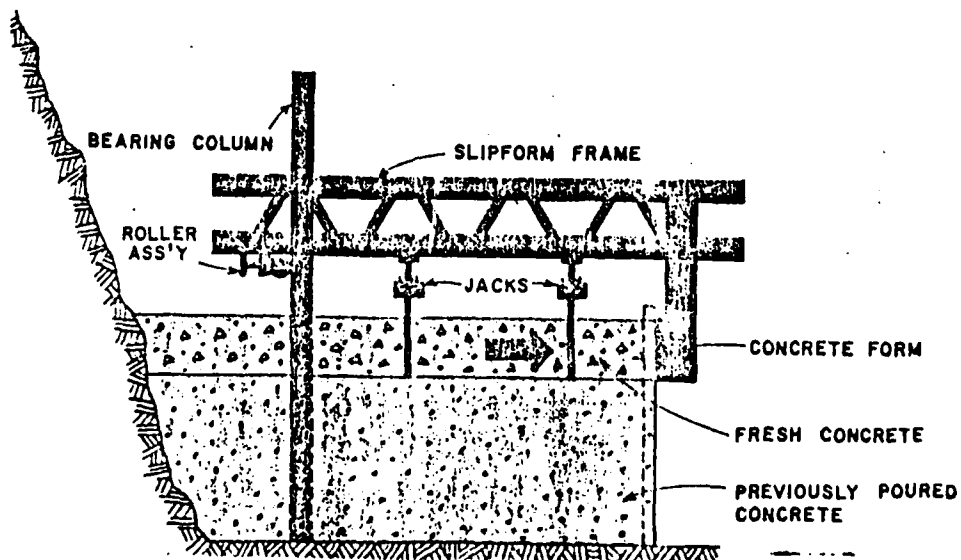


Figure 23 - Specially Constructed Slipform for Outer Face of Mass Concrete Placement
(Source: Constructing Methods & Equipment, June, 1977, p. 46)

include lifting equipment, various accessories, and are usually constructed of steel.¹¹⁶

In addition, various construction equipment supplier's, such as Linden-Alimak, specialize in providing slipforming equipment, slipform project analysis, and supervision of slipform operations.

CHAPTER FOUR

BASICS OF THE HORIZONTAL SLIPFORMING TECHNIQUE

Most horizontal slipforming involves a fixed form support such as rock or earth and a moving slipform machine. The slipform machine may or may not be self-propelled, and is usually supported by rails or earth berms. Typical applications of horizontal slipforming include the paving of highways and runways, and the construction of medium barriers, sidewalks, curbs, tunnel inverts, cast-in-place pipe, and canal linings.

4.1 SLIPFORM PAVING

4.1.1 Slipform Paving Equipment

Slipform pavers are the single most common form of horizontal slipform machine, with over 38 different models available in America alone.¹¹⁷ Slipform pavers are not to be confused with the side-form pavers that were predominant in the paving industry about 20 years ago. In side-form paving, the steel rails were incorporated into side forms which contained the concrete and set the finished grade for the pavement. In slipform paving, the forms move with the paving machine, and the final grade is determined by built-in sensors.

A slipform paver is essentially a single self-propelled machine which takes concrete in via a chute, distributes the concrete along an auger shaft, and passes over the concrete thereby molding it to approximately the correct shape while vibrating and compacting it. Trailing forms attached to the paver give the concrete its final shape with smooth vertical sides, and a smooth top surface. Figures 24 and 25 show a slipform paver in operation. Concrete used with a

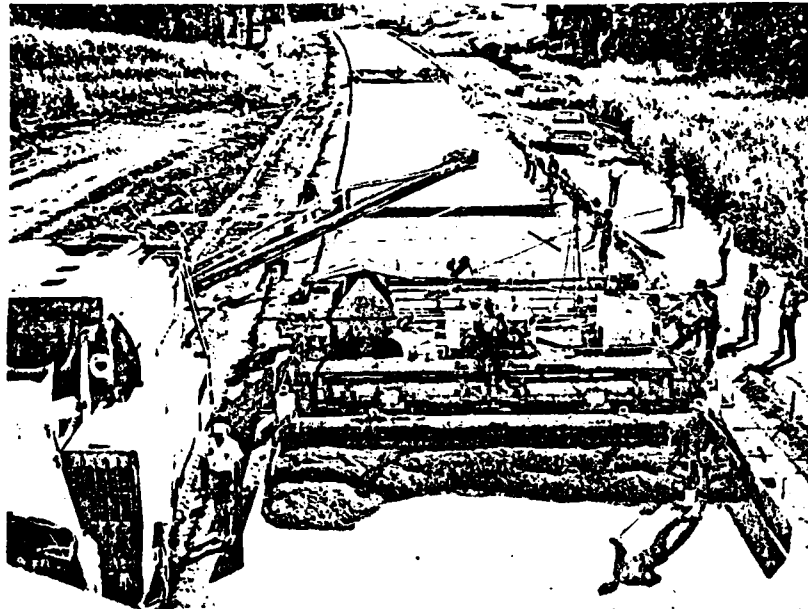


Figure 24 - Front View of Slipform Paver in Operation (Source: Oglesby and Hewes, Highway Engineering, Second Ed., John Wiley & Sons, New York, 1966, p. 701)

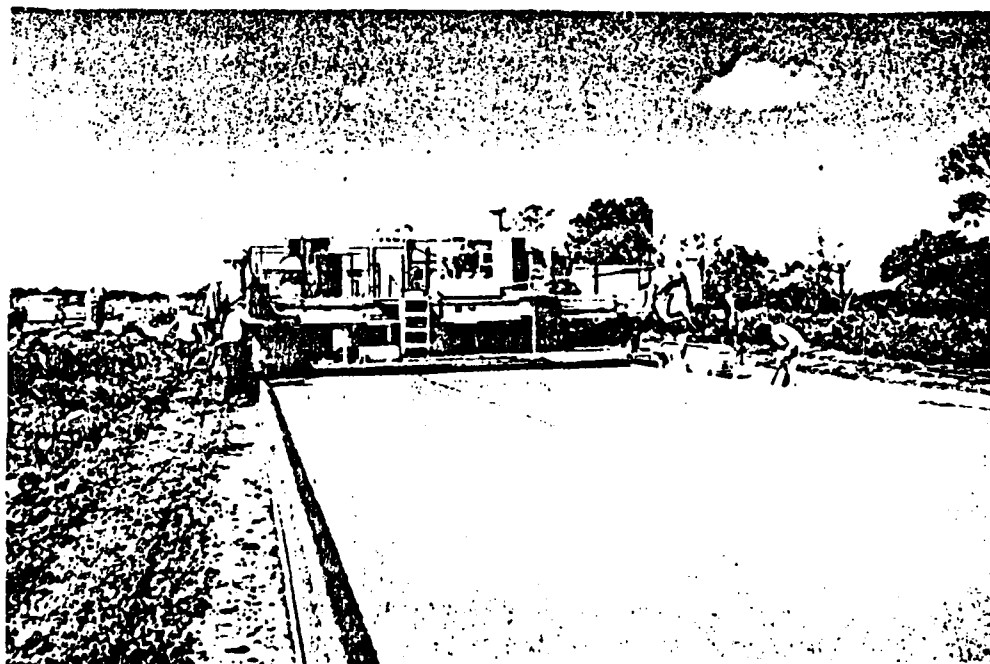


Figure 25 - Rear View of Slipform Paver in Operation
Source: Nunnally, Managing Construction Equipment, Prentice-Hall, New Jersey, 1977, p. 182)

slipform paver must be carefully controlled with a uniform consistency. The slump employed is between 1 inch and 4 inches, with a 1-2 inch slump being preferred.¹¹⁸ The concrete is placed on a prepared base. Typical slipform pavers can produce concrete pavements from 6 to 54 feet wide, and 6 to 20 inches thick.¹¹⁹ Maximum operating speed for these machines varies between 10 and 60 feet/min.¹²⁰

Slipform pavers are available today with such capabilities as adjustable single lane and dual lane capability, automatic grade setting, automatic steering, automatic profile monitoring, the ability to pave curb and gutter on a single pass, the ability to transition from a crowned cross section to a straight cross section without stopping, the ability to adjust pavement width on one machine from 6 feet to 50 feet, and accessories to allow the paver to be used on reservoir slopes up to 1.25 to 1.¹²¹ Some slipform pavers operate as combination fine graders and slipformers.¹²²

4.1.2 Slipform Paving Operations

Although operation of the equipment used in conducting slipform paving operations may appear to be straight-forward, there are several management pitfalls which can cripple a project.

For slipforming to be used to the maximum advantage, the width of the pavement should remain relatively constant since the pavers can't readily be adjusted to varying widths.¹²³ Variations in grade should be gradual and infrequent, and the minimum radius must be checked to ensure capability of paver to negotiate the turns.¹²⁴

The ideal length for a slipform paving project is between 7 and 10 miles, depending on local conditions.¹²⁵

With lesser project lengths, the full economic potential of the paver is not realized, while longer projects start to incur problems with concrete transportation cost and control.

However, the key ingredient to success in most slipform paving projects is speed. Contractors have been able to lay over 15,900 feet of 24 feet wide pavement in 20 hours. To maintain that pace the availability and coordination of aggregate, batching capacity, materials stockpiling, and materials delivery is critical. In another record-setting project, over 16,390 cubic yards were placed in 16 hours. (6,013 ft. of 17 to 21 inch thick pavement, 50 feet wide) That is a rate of over 1024 cubic yards per hour. On such large volume projects, a sufficiently large fleet of trucks is required to reduce the risk of halting the paver for lack of concrete. Queuing theory equations can be used to help decide the appropriate number of material haulers.

Aggregate stock piles and cement supplies need to be replenished constantly, and aggregate moisture content and gradation need to be monitored continually.

Even with proper planning and operational control, the contractor must take all feasible steps to ensure the paver will not break down during operations. Some contractors have on the job site a mechanical engineer or other machinery repair expert in order to minimize downtime.

Operator carelessness can lead to costly errors, since there is practically no room for profile error, and the expense of grinding down bad sections can be prohibitive.¹²⁷

The slipform paver is usually followed by two gantry type pieces of equipment, one carrying the finishers and a second gantry to apply curing compound. The finishers work the surface with large bullfloats.

With respect to reinforcing steel for concrete slipformed pavements, the steel dowels used at the construction joints are usually pre-assembled into dowel baskets and nailed to the earth base at predetermined joint locations. The slipform paver places and shapes the concrete over the dowels. Between 6 and 30 hrs. after the paver has passed, a concrete saw crew cuts construction joints in the green concrete.¹²⁸

For those pavements requiring continuous reinforcement, the paving train will include a spreader in front of the slipform paver. The spreader will receive the concrete from the trucks and spread the concrete to approximately one half the final pavement depth. (The spreader will pass over the dowels.) After the spreader has passed a crane will place a section of steel reinforcing mat on the fresh concrete. The slipform paver, which follows about 50 feet behind the spreader will then bring the concrete to final shape and grade.¹²⁹

When dowel ties are needed to tie the pavement slab to a subsequent, adjacent lane, they can be inserted by the paving machine, or be inserted by hand into gang-drilled holes, a few hours after the paver has passed.

4.1.3 Ramp, Curb, Gutter, Sidewalk, and Median Paving

Slipform paving machines are also used to pave ramps, curb, gutter, sidewalks, and median barriers.

In many cases, the chief difficulty with ramp paving has been ramp design modifications in order to successfully employ slipforming

techniques. If ramps are designed originally, so that the slipform pavers can be used, the owners can realize a significant economic savings. The recommended ramp design features include:¹³⁰

- (a) Uniform pavement width
- (b) Minimize length of tapered section
- (c) Construction of a sufficiently wide subbase to support a 24 feet wide slipform paver, regardless of pavement width
- (d) The elimination of reinforcing steel from ramp pavement
- (e) Construction of a stabilized subbase that concrete delivery trucks can use
- (f) Greater range of tolerances than those required of mainline pavements
- (g) For ramps with curbs, a provision for attaching the curb to the pavement at a later date, as an alternative method to integral pavement and curb construction.

In addition to the numerous slipform pavers that can produce curb and gutter sections simultaneously with the main pavement surface, there are at least six different slipform machine models available in America that specialized in curb, gutter, and barrier wall placement.¹³¹ These machines have operating speeds which vary from 25 to 60 feet/minute, and some can extrude barrier walls up to 65 inches high.¹³² The general minimum radius that these curb and barrier slipformer pavers will negotiate is approximately 7-15 feet.¹³³ Figures 26 and 27 illustrate typical slipform machines used for constructing curbs and barriers. Since these machine involve relatively small daily volumes of concrete, they are used in conjunction

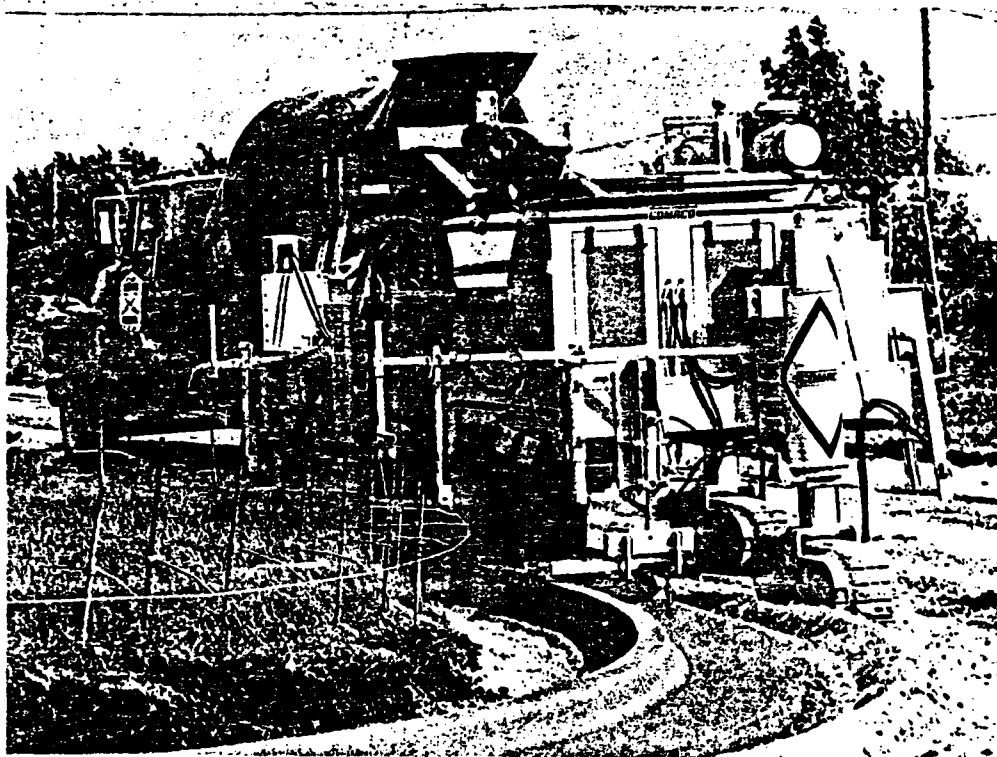


Figure 26 - Curb Being Produced by Specialized Slipform Machine
(Source: Gamaco Inc., Ida Grove, IA, Pamphlet, 1979)

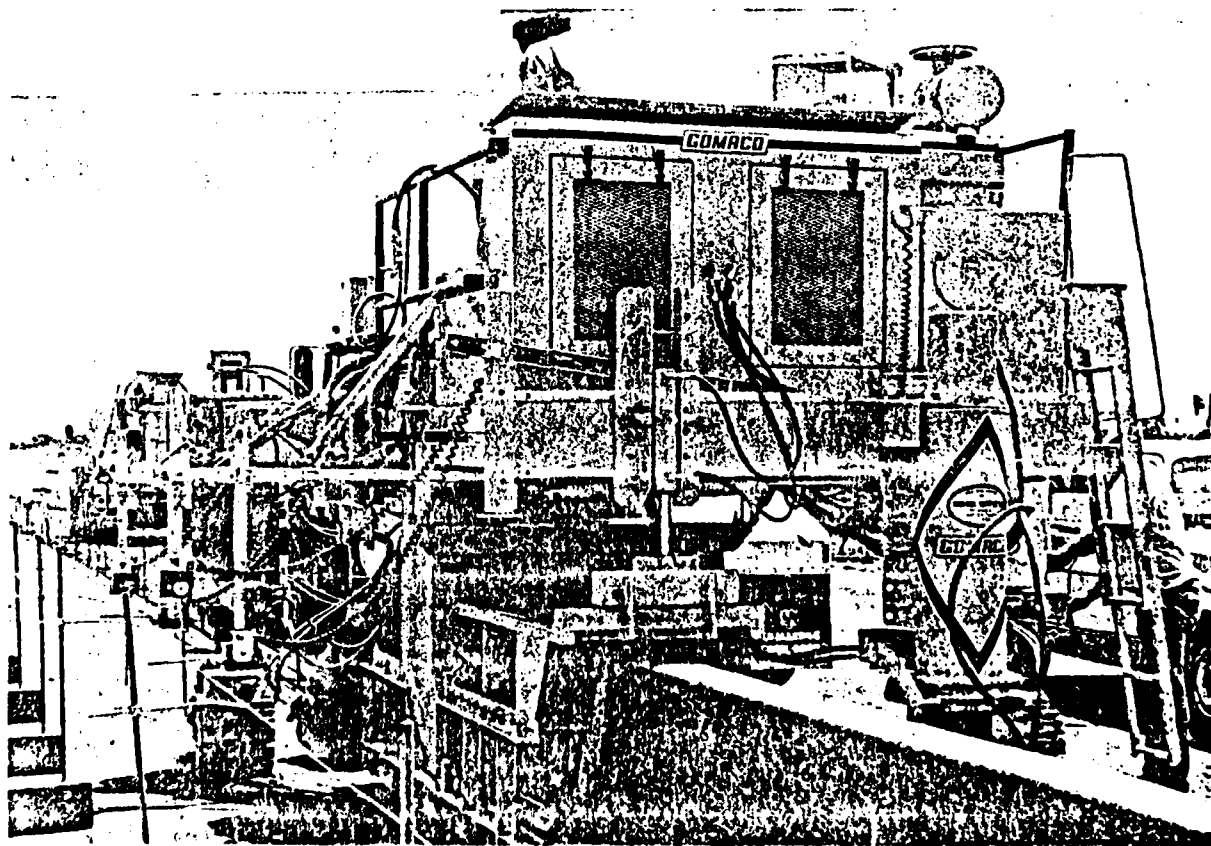


Figure 27 - Barrier Being Produced by Specialized Slipform Machine
(Source: Gomaco Inc., Ida Grove, IA. Pamphlet, 1980)

with transit mixers.

Curb and gutter machines typically slipform 2500 feet/day, although as much as 11,440 feet have been placed in 11 hours.^{134,135}

4.1.4 Canal Lining

There are several different methods of slipforming canal and channel linings. One very simple method involves conventional paving of the horizontal canal floor, and the use of a weighted steel pan to form the slope linings. The steel pan or slipform screed is pulled or winched, up the slope, over low-slump concrete while a hand-held immersion vibrator is used to compact the concrete just in front of the screed. The form itself is not vibrated since this would cause a swell wave in the concrete just emerging from the trailing edge.¹³⁶

Figure 28 illustrates the operation of a slipform screed.

Numerous sophisticated slipform pavers are available to line canals and channels at a single pass. These full section canal lining machines are used on canals with up to about 50 feet of total lining width. Larger canals are lined in half sections, or the slopes and bottom deck are constructed separately.

Canal lining machines operate much like the conventional pavers, but have a transverse, compartmented trough for uniformly distributing the concrete on the slope.¹³⁷ Sometimes a distributor plate is attached to the leading edge of the slipform, while other machines use a continuous row of hoppers, each supplying one compartment of the trough below. Concrete is usually delivered to the hoppers or trough compartments by a shuttle car on the working platform.¹³⁸

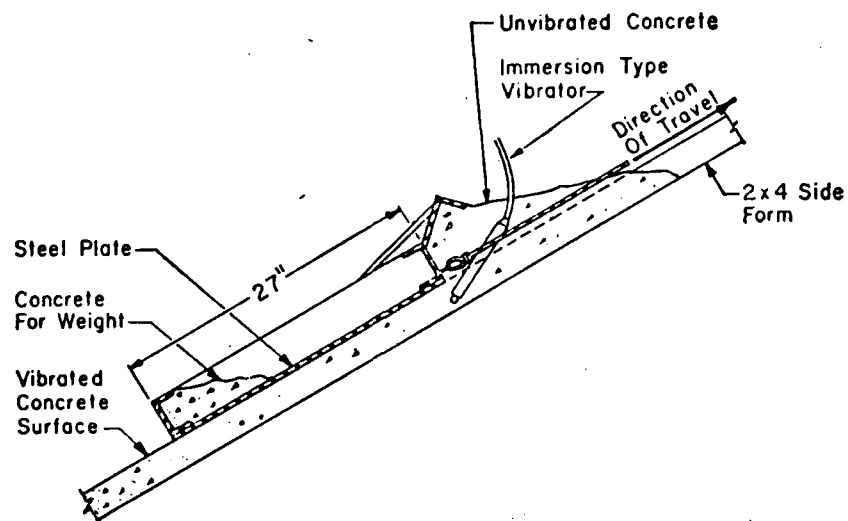


Figure 28 - Slipform Canal Wall Screed
(Source: Hurd, Formwork for Concrete, American Concrete Institute, Detroit, MI, 1973, p. 290)

After the concrete passes through the trough, it is consolidated by a vibrating tube parallel to and just a few inches in front of the slipform. The trailing edge of the slipform is set at a position lower than the leading edge which tends to further improve concrete consolidation.¹³⁹ The concrete consistency must be even more carefully monitored than that for conventional road pavement, with low slump concrete being used. Another key consideration, is whether or not the slipforms have enough weight to resist hydrostatic uplift.

4.2 Cast-in-Place Pipe

Various slipform machines are available to cast pipe in place for such uses as drains, highway culverts, aqueducts, sewers, and even underground missile passages. The NO-Joint Pipe Company¹⁴⁰ for instance, has machines available to case pipe in sizes from 24 inch in diameter to 120 inches in diameter in 6 inch increments. The machines manufactured by this company consist of a mandrel assembly which has as its components; an inside bottom form, an outside top form, and a hopper. The mandrel rides on a steel sled along the bottom of the trench. As the self-propelled machine advances, semi-circular, collapsible, aluminum forms 4-6 feet long are fed into the front of the mandrel and manually attached to the preceding form. These collapsible forms together with the outside top form of the machine produce the upper 230 degrees of the pipe. The rest of the pipe is formed by the machine's inner slipform and the base of the trench. The concrete is discharged from the hopper down around the forms by an electronically powered spading device. The concrete is also vibrated.

The collapsible forms are left in place for 4-6 hours after the concrete placement.

This machine has produced 120 inch diameter pipe with walls 12 inches thick at the rate of 30 feet/hour.

The R.A. Hansen Company has another type of cast-in-place machine to slipform large diameter concrete pipe in place. This machine works essentially the same as that described in the previous section, with the concrete being produced between the upper slipform, the circular inner form, and the trench walls. However this machine includes a forward trench scraper, and a mobile truck ramp system for unloading large bottom-dump trucks. A 16 meter long rubber-tired form transporter recovers the inner forms for reuse several hours after the slipform machine has passed. This system has been used to case nearly 700 feet of 14.3 feet diameter pipe with an 8 inch wall thickness in only 8 hours. That placement required the use of 700 feet of collapsible inner forms.

4.3 Tunnel Inverts

Slipform machines are often used¹⁴¹ to place a continuous tunnel invert. The invert is shaped to a predetermined diameter, and a curved paving machine rides over the invert slipforming a layer of concrete.

The slipform can be moved forward by winches or in some cases, is self-propelled. The concrete is usually delivered by pump or conveyor belt and is placed just ahead of the slipform. Hurd¹⁴² recommends that the best way to hold the concrete to a true arch shape, is to vibrate well the concrete along the sides of the form, and to use a heavily weighted

slipform which has a length equal to or greater than the width of the invert.

4.4 Miscellaneous Uses

Horizontal slipforms can also be used for surfacing bridge decks, sidewalks, breakwaters, and warehouse slabs. As stated earlier, the variety of uses is limited only by the imagination. Perhaps one of the more unique uses of a horizontal slipform machine is in the construction of risers for fieldhouses and stadiums. H.A. Lott slip-formed 30 rises for a 15,000 seat fieldhouse 8 weeks ahead of the scheduled time allowed for conventional methods.¹⁴³

There are also slipform pavers available which will can pass over obstacles through the use of hydraulic arms and an articulated joint frame.¹⁴⁴

Future development of horizontal slipform machine may include the use of slipform pavers in concert with surface planers, to give a one pass surface rehabilitation or overlay treatment.

CHAPTER FIVE

ECONOMIC ASPECTS OF SLIPFORMING

5.1 Economic Aspects of Vertical Slipforming

Vertical Slipforming can result in a significant cost savings for the owner and contractor. However, slipforming is not always the most economical concrete placing method. Although many people assume that structures over 60 feet high are ideal candidates for slipforming, J. F. Camellerie of Ebasco Services, Inc. states that some structures over 500 feet high cannot be economically slipformed. Although, in general, the higher the building, the lower the unit form cost; consideration for the volume of concrete needed is also important.¹⁴⁴ The ideal slipform project would involve a structure requiring 20-30 cubic yards of concrete per foot of elevation, light reinforcing steel, and no openings or inserts.¹⁴⁵ Mr. Camellerie cautions further that it is necessary to consider slipforming as only part of an overall project system. A lower formwork cost does not necessarily translate into a lower total project cost.

However, vertical slipforming usually does result in a major savings in the cost per square foot of form contact area.¹⁴⁶ Normally a set of 4 foot high forms will last for 400 feet of slipforming, which results in a reuse factor of 100.¹⁴⁷

The other major advantage of slipforming is speed. Vertical slipforming is generally quicker than other vertical forming methods, and has been responsible for significantly reducing construction times by over 25% on several large projects. Perhaps the most recent

example of the success afforded by slipforming is the \$125 million Executive Center Project in Honolulu, Hawaii. Project manager, Albert Fink states that vertical slipforming saved \$100,000 in the first 6 floors alone of the 41 story tower. Slipforming is also credited with shaving 1 month off the construction time.¹⁴⁸

Of course, to realize the full economic potential of vertical slipforming the contractor must be able to place the required amount of steel without interfering with the form slide-rate. Tight material delivery schedules are also required.

In fact slipforming forces the contractor to plan the entire project more thoroughly.¹⁴⁹ It is critical that the formwork not make any unscheduled stops.

In areas which undergo severe weather extremes, close scrutiny of the mix is essential. During one slipform project, which was being performed in a widely varying climate, the contractor had 5 different mix designs available, the choice depending on the temperature.¹⁵⁰

Despite all the precautions, vertical slipforming is not considered to be a difficult technique for contractors to learn.¹⁵¹ In fact the success rate is very high among contractors using this method.

There is some disagreement among slipforming experts, as to the necessity to employ workers overtime in order to reach the full economic benefits of slipforming. Slipforming can be successfully accomplished without resorting to continuous placements, or overtime, but there are other times when a tight schedule must be met despite the premium of overtime costs.

Additional economic benefits which are side-effects of slipforming operations include, decreased crane capacity requirements, decreased finishing costs, and increased crane hoisting time available.

Tables 4 and 5 show the relative costs associated with different concrete casting systems. The tables show that with respect to the construction of high-rise buildings, (approximately 60 feet or more in height) slipforming has a lower average labor cost than either: cast-in-place concrete, precast panels, combination precast and conventional forms, and combination slip and gang forms. With respect to medium-rise buildings (approximately 20-60 feet in height) slipforming is no longer the clear choice. In fact, for medium rise buildings, several of the other methods of concrete casting have a lower labor cost.

As Table 5 outlines, overall system comparison show slipforming as having a lesser cost factor, than any of the other 4 systems shown with the single exception of precasting. Note, however, the significant savings in construction time that slipforming gives when compared to the other systems being analyzed. With today's interest rates, the cost of financing a project is substantial and finishing on or ahead of schedule can make the difference between a loss and a profit.

There is an unfortunate misconception by many contractors that vertical slipforming involves unreasonably high start-up costs, highly specialized training, round-the-clock operations, and overtime premiums. Until more contractors are educated as to the potential profitability of vertical slipforming, many contractors are going to be convinced that slipforming won't save them money.

5.2 Economic Aspects of Horizontal Slipforming

A contractor cannot compete today in mainline paving without using a slipforming machine.¹⁵² In fact, some contractors estimate a 50%

Forming System	Average Comparative Cost Factors	High-Rise Building			Medium-Rise Building		
		Average Labor Cost	High Labor Cost	Low Labor Cost	Average Labor Cost	High Labor Cost	Low Labor Cost
Cast-in-Place Gang Forming	1.00	.96	1.14	.75	1.04	1.26	.82
Conventional Form + Precast Panels	1.02	.98	1.16	.79	1.06	1.26	.86
Combination of Slip and Gang Form	.98	.94	1.12	.75	1.02	1.21	.82
Slipform	.96	.86	1.02	.69	1.06	1.20	.83
Precast	.96	.95	1.04	.78	.97	1.09	.80

Figure 4 - Cost Comparison by Casting System

(Source: Fintel, Handbook of Concrete Engineering, Jan Nostrand Reinhold, New York, 1974, p. 706)

Placing System	Comparative Cost Factors	Finish*	Concrete Joints	Construction Time Factor	Safety*	Construction Tolerance		Special Features
						Plumbness	Wall th'k	
Cast-in-Place Gang Forming	1.00	A-	horizontal and vertical	1.00	B	1"	-14", +12"	No Special Skills Required
Conventional Form + Precast Panels	1.02	A+	horizontal and vertical	1.00	B+	1"	-14", +12"	Precasting at Yard
Combination of Slip and Gang Form	.98	A-	horizontal and vertical	.75	B+	3"	-12", +12"	Forming Operation + Conventional Slip Forming
Slipform	.97	A+	none	.40	A-	2"	-14", +12"	Special Skill and Equipment Required
Precast	.94	A+	horizontal	.50	A	12"	-14", +12"	1. Winter Protection at Grade. 2. Inspection at Grade.

* Finish rated as follows: Uniform finish without tie holes - A+
Uniform finish with tie holes - A-

** Safety rated as follows: Work mostly on ground or solid platform - A
Work mostly on scaffolding - B

Table 5 - Cost Comparison of Casting System for a Specific Building

(Source: Fintel, Handbook of Concrete Engineering, Van Nostrand Reinhold, New York, 1974, p. 706)

savings over the once conventional paving methods.¹⁵³ As stated earlier, the optimal horizontal slipforming job would be a straight stretch of multi-lane highway 1-10 miles in length. Some contractors, however, set a minimum total cubic yardage before they will consider undertaking a slipform paving project. Some contractors set a minimum volume as high as 300,000 cubic yards while others will take jobs as small as 1500 cubic yards total volume or $\frac{1}{2}$ mile in length.¹⁵⁴

Horizontal slipforming is usually performed by a specialty contractor or sub-contractor, since the equipment required represents a minimum investment of \$1 million. The minimum investment jumps to over \$3 million if the contractor wants to own his own batch plant.¹⁵⁵

Horizontal slipforming is very unforgiving when it comes to contractor error. A small profile error can cost hundreds of thousands of dollars to correct.¹⁵⁶ On the other hand, slipforming requires 30 to 40 fewer laborers than a typical paving machine and can pave at a rate which is 60% greater.¹⁵⁷

Horizontal slipforming is universally recognized in America as being far more economical for roadway paving than fixed form or side form methods. The fact that the construction industry is expanding the use of horizontal slipforming into areas previously done by fixed form methods, is a positive endorsement of the profitability of this technique.

CHAPTER SIX
CONCLUSIONS/RECOMMENDATIONS

6.1 Vertical Slipforming

The advantages of vertical slipforming over conventional casting systems includes:¹⁵⁸

- (a) Accuracy
- (b) Fewer construction joints
- (c) Ability to cast a monolithic structure
- (d) Can be used with almost any shape in plan
- (e) Superior strength
- (f) High quality finish with fewer finishers
- (g) Speed
- (h) With proper planning and design, slipforming can result in a lower crew size
- (i) Uses less formwork materials, while maximizing form reuse
- (j) Most economical method of construction for certain types of high-rise buildings, towers, and chimneys
- (k) Lends itself well to producing aesthetically pleasing structures
- (l) Reduces crane sizes required.

The disadvantages of vertical slipforming include:¹⁵⁹

- (a) Good job site planning and supervision required
- (b) Large quantities of equipment, such as jacks, lights, are required, level monitoring equipment, and hoisting equipment

- (c) May require round-the-clock operations to maximize profit
- (d) Employees must become trained in use of the equipment and methods
- (e) Operations must be continued despite bad weather
- (f) High initial cost
- (g) Round-the-clock operations necessitate 24 hour canteen services, and material supply
- (h) Communication between ground level crane operators, and slipform operators is critical
- (i) The need for continuous operations, either during the regular workday, or round-the-clock creates labor union problems
- (j) Placement of reinforcing steel must be carefully detailed and supervised
- (k) A minimum amount of time to form openings
- (l) Workers needed on the job before and after the daily slide operations
- (m) Less site control if specialty subcontractor required for slipforming
- (n) Slipforming leaves less room for error, and mistakes tend to be costly.

Vertical slipforming is primarily a time saving method, which, in saving time, can save the owner and contractor significant sums of money. It is best employed in the construction of tall chimneys, towers, and building cores requiring approximately 20-30 cubic yards of concrete for each foot of elevation.

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CONCRETE CONSTRUCTION USING SLIPFORM TECHNIQUES(U)
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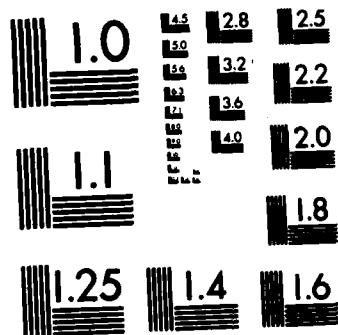
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Since the forms are usually only 4 feet deep most slipforms can be economically constructed and still achieve a relatively high factor of safety. Therefore, calculation of lateral forces tends not to be critical.

A paucity of comprehensive, educational literature exists on the subject of vertical slipforming, even though several large companies have been successfully employing the technique for several decades. The use of this technique has really mushroomed in the last 15 years, and demand for comprehensive data concerning the technique is surely to increase. It is recommended that engineering students be exposed to this and other innovative yet important construction techniques, during the course of their studies at engineering schools, and that more research dollars be spent to study the execution of innovative and state-of-the-art construction techniques.

6.2 Horizontal Slipforming

That portion of the horizontal slipforming technique that involves road paving is generally accepted throughout the construction industry, as the fastest, most profitable method of paving concrete structures that is now available. However, the slipforming or extrusion of barriers, median walls, curbs, gutters and concrete pipe is just beginning to exhibit its potential. Much has been achieved in the slipforming of horizontal structures during the last 10 years. Yet the ever-increasing cost of labor indicates that even greater use of concrete slipforming and extrusion techniques will be achieved.

Perhaps the greatest problem facing the practitioners of horizontal slipforming is the availability of a sufficient supply of materials.

The larger slipforming machines can place more concrete than the contractor can supply. It appears that the weak link in horizontal slipforming is the delivery system design and control.

Slipforming requires the best of our resource management skills and equipment management techniques.

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APPENDIX A
DATA REFERENCE

Specs Concrete slipform pavers

Make	Model	Standard Engine										Dimensions						
		Type Automatic Control System:		Electronic (E), Electro-Mechanical (E/M), Hydraulic (H)		Operating Speed (rpm)		Operating Weight		Make		Model		Rated HP		Height (ft-in)		
		Max. Paving Width (ft-in)		Min. Paving Width (ft-in)		Barrier Configurations Available		Max. Operating Speed Available		Max. Travel Speed (rpm)		Gutter Configurations Available		Overall Width (ft-in)		Length (ft-in)		
		Crawler or Wheel Type		Paving Depth (in)		Paving Depth (in)		Paving Depth (in)		Paving Depth (in)		Paving Depth (in)		Paving Depth (in)		Paving Depth (in)		
Harbor Green	UH 11	C	8-0		54	Yes	Yes	25	100	14,500	E/H	Deere	219CD	70	7-8	10-11	6-8	
GOM	SF-250	C	32	12	10	Yes	No	35	80	47,000	H	Cat	D-3208	208	31-0	10-0	10-6	
	SF-500	C	24-0		20	Yes	No	60	180	115,000	H	Cat	D-3406	375	29-3	40-1	10-2	
	Suburban	C	28-0		18	Yes	No	60	180	72,000	H	Cat	D-3306	250	40-0	30-8	9-6	
	Super 200	C	16-0	10-0	10	Yes	Yes	25	60	29,500	H	Cat	D-3208	142	20-1	20-2	8-6	
	SF 175	C	10-0	0-7	10	Yes	Yes	60	180	19,500	H	Cat	D-3298	142	8-0	21-6	9-4	
GOM	GTO300 Trimmer/Paver	C	7-6	0-8	65	Yes	Yes	45	80	20,000	E	GM DD	371	113	8-0	21-8	8-6	
	GP 2500 Paver	C	25-0	17-0	10	Yes	Yes		45	40,000	E/H	GM	471	160	32-0	12-0	12-8	
	HW105 Paver	C	20-6	7-6	10	Yes		45		24,000	E	GM DD	471	160	5-5	8-4	9-0	
	CS2400 Spreader	C	20-6	7-0	7-0			45			E	GM DD	463	87	5-5	8-4	9-0	
	GTO300/78 Trimmer/Paver	C	4-0	0-8		All	Yes	45	80	11,000	E	GM DD	353	64	7-4	11-5	8-2	
	GTO300/90 Trimmer/Paver	C	5-0	0-8		All	Yes	45	80	11,300	E	GM DD	353	64	8-4	11-5	8-2	
	BP6400 Blower	C					Yes	40	40	35,000	E			160	10-0	24-0	12-0	
GOM & Zimmerman	MSP 30	C	10-0	5	9	Yes	Yes	16	65	21,000	E	Deutz	F4L912	80	15-0	12-0	9-0	
	MSP 50	C	16-5	18	12	Yes	Yes	10	30	28,600	E	Customer Choice		70	20-0	17-0	9-0	
	MSP 85	C	28-0	14	18	No	No	10	65	55,000	E	Customer Choice		110	38-0	24-0	10-0	
	MSP 150	C	50-0	12	20	No	No	19	62	121,000	E	Customer Choice		260	58-0	13-6	13-0	
GOM	AT 1100 Curb Cutter	C	4-0	0-0	21	Y	No	30	100	14,000	E/H	Deere	4319	52	7-11	13-6	9-5	
	AT 9000	C	24-0	8-0	12-0	Yes	Yes	12	70	33,000	E/H	Deere	6414	113	8-0	26-0	9-6	
	AT 7500 Curb quipper	C	7-0	6	59	Yes	Yes	C/30 W/30 C/30 W/30 P/12	70	24,000	E/H	Deere	6414	113	8-0	17-1	9-9	
	8100	C	16-0	6	59	Yes	Yes		70	35,500	E/H	Deere	6414	113	8-0	17-10	9-9	
Pac Power	Outpost		20-0	12-0				12	26	24,000					23-4	7-0	8-0	
	1220		20-0	12-0				12-0		14,000					22-2	14-0	7-0	
	1626		26-0	16-0				12-0		17,000					26-2	14-0	7-0	
POWER CAT	6700	C	10-0	0-6	10	Yes	Yes	45	80	15,000	E/H	Deere	4238	76	8-0	16-5	7-7	
GOM	HS 24C	C	25-0	11-0	6	No	Yes	15			E/H	Cat	D 330	110				
	HS 50C	C	41-0	25-0	6	No	Yes	15			E/H	Cat	D 330	110				
	HS 400C	C	14-0		6	No	Yes	15			E/H	Cat	D 330	110				
	HS 87C	C	23-0	36-0	6	No	Yes	15			E/H	Cat	D 330	110				
	HS35C	C	31-0	17-0	6	No	Yes	15			E/H	Cat	D 330	110				
	HS 26C	C	21-0	11-0	6	No	Yes	15			E/H	Cat	D 330	110				
	HS 31C	C	19-0	11-0	6	No	Yes	15			E/H	Cat	D 330	110				
	HTS 1C	W	18-0		6	No	Yes	15	21		E/H	Bedford	Gen	25Kw				
	HTS 2C	W	16-5		6	No	Yes	15	21		E/H	Bedford	Gen	25Kw				
	HTS 5C	W	20-0		6	No	Yes	15	21		E/H	Bedford	Gen	25Kw				
	S 20	C	20-0	8-0	7	No	Yes	10	20		E/H	Cat	3304	165				
	S 30	C	31-0	10-0	7	No	Yes	10	20		E/H	Cat	3304	165				
S 48	C	48-0	12-0	7	No	Yes	10	20		E/H	Cat	3606	250					
S 50	C	50-0	14-0	7	No	Yes	10	20		E/H	Cat	3306	250					
H&A	12'-20' Town & Country	C	20-0	12	14	Yes	Yes	60		48,000	E/M	Cat	D3304		24-2	19-4	11-8	
	20'-25' Town & Country	C	25-0	20	14	Yes	Yes	65		54,000	E/M	Cat	D3304		29-2	19-4	11-8	

APPENDIX B
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