Lateral Earth Pressure on Lagging in Soldier Pile Wall Systems

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Soldier pile and lagging is a conventional means of temporary excavation shoring. Timber lagging design has traditionally been based upon the designer's experience or empirical rules. One such method is the Goldberg Zoino chart used by the Federal Highway Administration. Most of these methods restrict the designer to a consistent soil profile, certain pile spacing, construction grade timber lagging, and limited depth. The methods do not take into account surcharge loads or a variety of other factors that could arise. A designer working outside of ordinary circumstances with unusual loads, varying soil conditions, or alternate lagging materials has difficulty estimating lateral earth pressures.

In rigid earth retention systems, lateral earth pressure is generally assumed to be constant along the length of the wall. In soldier pile and lagging systems, the lagging is often considerably less stiff than the steel soldier piles. As the lagging deflects, the soil tends to bridge between the stiffer elements resulting in a lower pressure on the lagging. Several previously published methods by others for determining this reduced pressure are summarized and discussed. These methods typically consist of using a portion of the active earth pressure in several different pressure distributions.

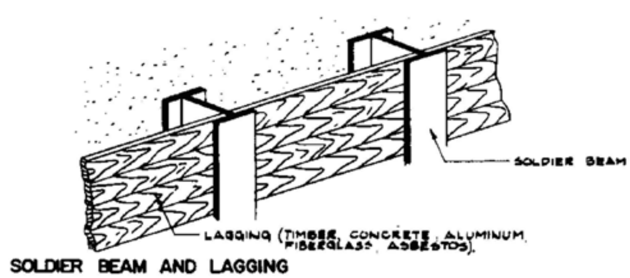
A simple theoretical model is presented for determination of lateral earth pressures on wood lagging. The model is based on a three-dimensional "silo" shaped sliding wedge analysis. Results of the model are compared with other published methods. The model compares well with these methods which cover the normal spectrum of design situations. In addition, the model can be used to estimate lateral earth pressures outside typical situations.

INTRODUCTION

Soldier pile and lagging walls are commonly used systems for supporting excavations in urban environments where property lines, roads, and utilities prohibit sloped or benched excavations. Soldier pile and lagging walls can be more economical and faster to construct than many other earth shoring systems. Excavations in excess of 30 m (100 ft) in depth have been successfully completed using soldier pile and lagging systems with tie-backs or bracing.

The main components of soldier pile and lagging excavation support systems are steel H-piles placed vertically at 1.22 m to 3.05 m (4 to 10 ft) on center with lagging placed between the piling to retain the soil. An example of a portion of a soldier pile and lagging wall is shown in Fig. 1. The lagging may consist of rough sawn timber, metal decking, or even pre-cast concrete planks. H-piles can be installed by driving, vibrating, or by drilling a hole and wet-setting the pile in a grout column at the bottom of the excavation. Soldier piles are placed prior to excavation. As the excavation is advanced, lagging is placed between the soldier piles.

In soils with some stand-up time, lagging can be drug from the top and pulled downward. In other soils, lagging is sometimes installed continuously on the outside of the piles. If sloughing or slight caving occurs, soil is packed behind the lagging.



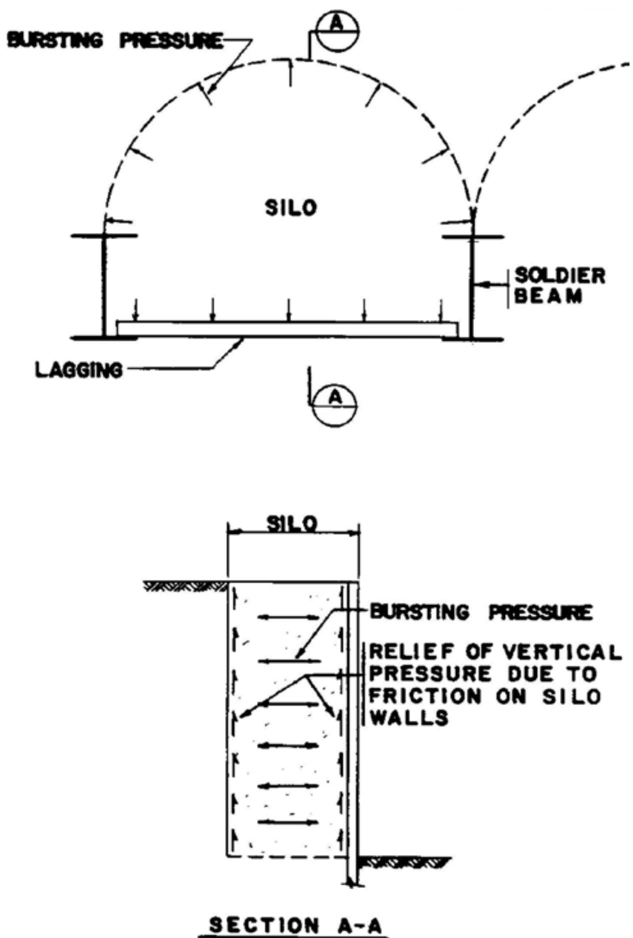
[FIG. 1] Portion of Soldier Pile and Lagging Wall System (US Navy, 1988)

Soldier pile and lagging systems are usually employed in competent soils and are not effective in soft clays or below the groundwater table where experience has shown that the soils cannot arch between piles.

TRADITIONAL DESIGN METHODS

It is well-known that soil arches between soldier piling creating a silo effect as shown in Fig. 2. Friction and cohesion along the sides of the "silo" resist sliding of the soil mass and thereby reduce lateral pressure. It is also well known by practitioners that the pressure on lagging approaches a constant at some depth for most soil conditions.

Lagging has traditionally been designed based upon experience or empirical methods. One method is a chart of recommended timber lagging thickness for different soil types, pile spacing, and wall heights. This chart was developed by Goldberg-Zoino and Associates to be used by the Federal Highway Administration for designing timber lagging. It is also referenced by the US Navy (1988). The chart is shown in Fig. 3.



[FIG. 2] Silo Effect for Soil Lagging (US Navy, 1988)

In the Goldberg-Zoino chart, soils are classified into three categories based upon their degree of competency. Timber lagging thickness is then selected from two or three depth categories and the lagging clear span. The maximum depth available on the chart is 60 feet. Determination of soil category is left to the judgment of the designer.

The Goldberg-Zoino chart does not address different species or grades of timber lagging. The chart provides no assistance for other types of lagging materials. Surcharge loads at the ground surface are not taken into account.

Another popular method of estimating the pressure on timber lagging has become known in practice as Terzaghi's trap door analogy. Terzaghi (1943) explained that when an opening is created in a structure containing soil, a shear zone is created above the opening. Soil above the shear zone is held in place by arching. Therefore, the load acting on the "door" of the opening is equal to the weight of soil below the shear zone. This soil weight is independent of the height of soil above the opening. Rather it depends only on the density and shear strength of the soil which defines the geometry of the shear zone.

In an unpublished document, Spencer, White and Prentis, Inc. (1986), stated that Terzaghi's trap door analogy could be extended to explain horizontal arching between soldier piles. They showed that mixed hardwood with 76 mm (3-inch) thickness and an allowable bending strength of 11 MPa (1600 psi) could span an unsupported distance of 2.9 m (9'-6") in sand soils with a friction angle of 30 deg. The pressure on the lagging did not depend on the height of retained earth.

The Terzaghi trap door analogy is useful because it takes cohesion into account. It gives a value of pressure on the lagging which can be used in design of different materials. The method has been used successfully for many years. However, its simple derivation causes some structural engineers to question its validity. It is difficult for some to make the leap from vertical pressure as derived by Terzaghi to horizontal pressure as suggested by Spencer, White and Prentis, Inc. Also, the method was not published in open literature to the author's knowledge. A more rigorous mathematical model subject to the scrutiny of professional publication may be beneficial to the industry.

Several other mathematical methods have been used to estimate the reduced soil pressure on the lagging. These methods typically consist of using a portion of the active earth pressure in different distributions. Two pressure distributions are shown in Fig. 4. The pressure distribution on the left side of the figure is based on a theory that the active earth pressure is a maximum at the soldier piles and a minimum midway between the piles. The pressure distribution on the right side of the

Recommended Thickness of Wood Lagging

Soil Description	Unified Classification	Depth	Recommended Thicknesses of Lagging (roughcut) for Clear Spans of: 5'	6'	7'	8'	9'	10'
COMPETENT SOILS								
Silts or fine sand and salt above water table.	ML SM-ML							
Sands and gravels (medium dense to dense).	GW, GP, GM, GC, SW, SP, SM	0' to 25'	2"	3"	3"	3"	4"	4"
Clays (stiff to very stiff); non-fissured.	CL, CH	25' to 60'	3"	3"	3"	4"	4"	5"
Clays, medium consistency and [gamma]H/ S[mu] < 5.	CL, CH							
DIFFICULT SOILS								
Sands and silty sands, (loose).	SW, SP, SM							
Clayey sands (medium dense to dense) below water table.	SC	0' to 25'	3"	3"	3"	4"	4"	5"
Clays, heavily overconsolidated fissured.	CL, CH	25' to 60'	3"	3"	4"	4"	5"	5"
Cohesionless silt or fine sand and silt below water table.	ML; SM-ML							
POTENTIALLY DANGEROUS SOILS								
Soft Clays [gamma]H/ S[mu] > 5.	CL, CH	0' to 15'	3"	3"	4"	5"	-	-
Slightly plastic silts below water table	ML	15' to 25'	3"	4"	5"	6"	-	-
Clayey sands (loose), below water table	SC	25' to 35'	4"	5"	6"	-	-	-

Note: In the category of "potentially dangerous soils," use of lagging is questionable.

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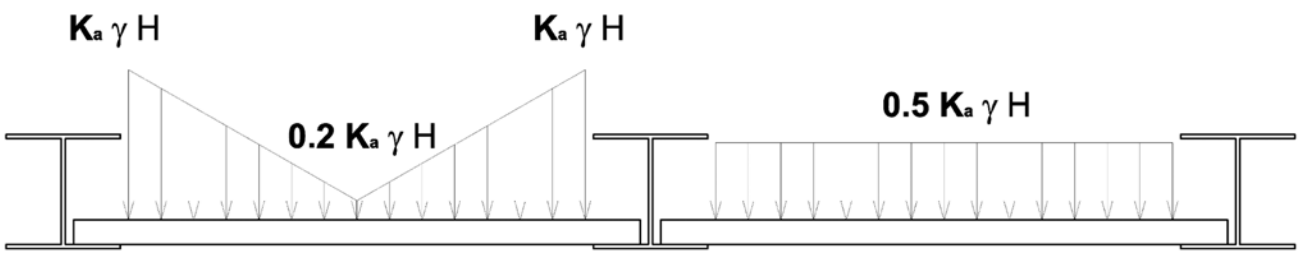


[FIG. 4] Reduced Soil Pressure Diagrams on Lagging (MacNab, 2002)

figure is based on a theory that the pressure on the lagging is equal to half the active earth pressure. According to both methods the pressure exerted on the lagging increases proportionally with depth without limit, which is contrary to experience.

DEVELOPMENT OF MATHEMATICAL MODEL

Mechanics of the soil semi-silo pictured in Fig. 2 cannot be analyzed using conventional grain silo theory as described in Bowles (1988). Static grain silo theories ignore friction along the sides of the silo. Dynamic theories are based on flow of grain down the center of the silo and resulting conical wedge that adds to hoop stresses.

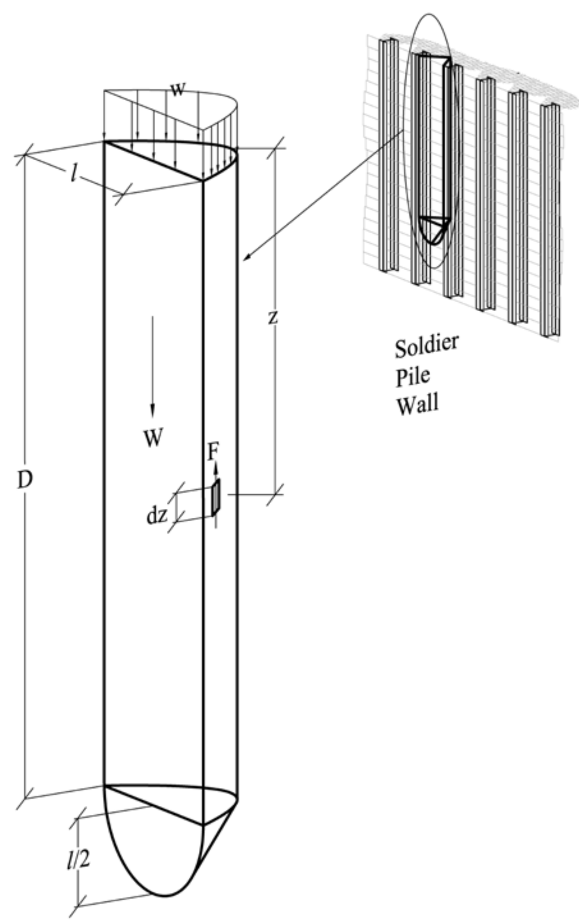
The earth pressure acting on timber lagging can be modeled using a sliding wedge analysis. A number of assumptions can be made to simplify the model. First, it is assumed that the soil bridges between the piles creating a silo of soil behind the lagging with semi-circular cross section as shown below in Fig. 5. It is further assumed that the bottom of the silo has a wedge shape opening toward the lagging. The shape shown in Fig. 5 is chosen because it is a simple combination of surcharge over a small active earth wedge.

The vertical "surcharge" pressure, Fv, acting on the small wedge at a depth D is the weight of the column of soil, W, and any uniform surcharge acting upon it minus the friction along the sides of the "silo". The friction of surrounding soil can be integrated over the surface area of the cylinder. Friction along the front of the "silo" against the lagging is ignored to be conservative and also because the lagging often can slide with respect to the pile. The vertical "surcharge" force of the columnar silo is given by

$$F_v = W + wa - \int_0^D \frac{1}{2}\pi T l \, dz \qquad (1)$$

where

- W = weight of soil silo = $aD\gamma$
- w = uniform distributed surcharge load
- a = cross-sectional area of silo = $1/8\ \pi l^2$
- D = height of silo
- T = shear strength of soil = $\gamma z K_a \tan(\varphi)$
- l = lagging clear span
- K_a = coefficient of active earth pressure
- γ = unit weight of soil
- φ = internal angle of friction



[FIG. 5] Soil Wedge Geometry

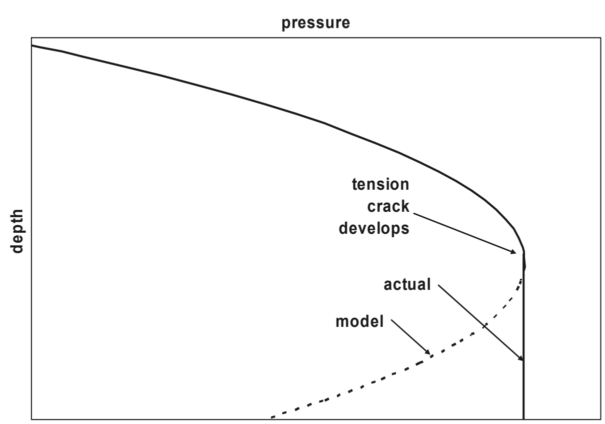
The angle of the bottom of the wedge relative to horizontal would be 45+(φ/2) according to Rankine. The slope of the bottom wedge can be approximated as 45 degrees in the model for simplicity of integration. As long as the earth pressure is still computed based on Rankine, the only effect of this geometric simplification is a slight change in depth of the "silo". The horizontal pressure, P, on the lagging at a depth D+ l/2 is the active earth pressure on the small bottom wedge and the vertical surcharge pressure, F_v/a, times the active earth pressure coefficient, Ka.

$$P = \frac{K_a \gamma l}{2} + \frac{F_v K_a}{a} \qquad (2)$$

After inserting Eqn. (1) and integrating the shear strength term, the lateral pressure at depth, D+l/2, is

$$P = K_a \left[\frac{l\gamma}{2} + w + \gamma D - \frac{2\gamma}{l} \left(K_a \tan(\varphi) D^2 \right) \right] \qquad (3)$$

A sample plot of lateral pressure distribution (Eqn. 3) shows that the pressure increases with depth to a maximum value where friction on the soil overcomes the driving force. In actuality, a tension crack will develop due to bridging and the pressure will remain constant with increasing depth.



[FIG. 6] Sample Results

The depth at which the maximum pressure on the lagging occurs can be found by taking the partial derivative of horizontal pressure (Eqn. 3) with respect to depth and setting the result equal to zero as shown below.

$$\frac{\partial P}{\partial D} = K_a \gamma \left[1 - \frac{4K_a \tan(\varphi)}{l} D \right] = 0 \qquad (4)$$

Solving for the silo height at which the maximum pressure occurs, D_{max}, yields

$$D_{max} = \frac{l}{4K_a \tan(\varphi)} \qquad (5)$$

The active earth pressure coefficient and tangent term are both functions of angle of internal friction, φ. If a new parameter is introduced, χ, such that

$$\chi = \left(4K_a \tan(\varphi) \right)^{-1} \qquad (6)$$

then Eqn. (5) can be re-written as the product of this new parameter and the free span of the lagging given by

$$D_{max} = \chi l \qquad (7)$$

If Eqn. (7) is substituted for D in Eqn. (3), the maximum pressure on the lagging, Pmax, can be found.

$$P_{max} = K_a \left[w + \frac{1}{2} l\gamma (1 + \chi) \right] \qquad (8)$$

Further simplifications can be made by examining the parameter, χ. A graph showing values of χ for various angles of internal friction, φ, is shown below. At very low values of friction indicating weak soils, χ can be as high as 5 to 7 or even higher. This (Eqn. 7) indicates the depth to maximum pressure is 5 to 7 or more times greater than the clear span of the lagging, *l*. Pressure on the lagging is also high. For most common granular materials, the angle of internal friction commonly lies between 15 deg and 45 deg. The value of χ is fairly constant over this range as shown in Fig. 7.

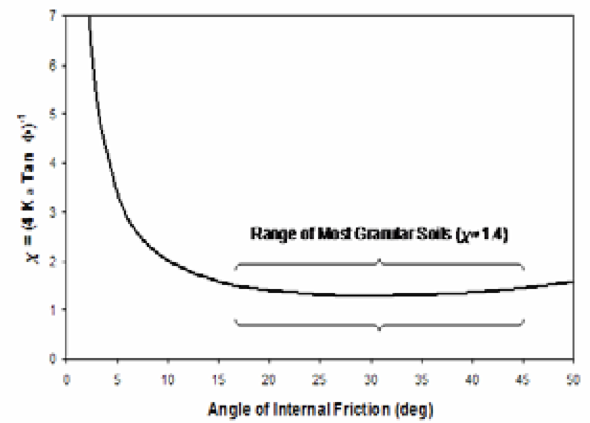
In fact, χ is within approximately +/- 5% of a constant value of 1.4 over the range of most granular soils. If χ=1.4 is substituted into Eqn. (7) and Eqn. (8), one obtains the following very simple equations for maximum pressure on lagging and the depth at which this pressure occurs and then remains constant.

$$D_{max} = 1.4l \qquad (9)$$

$$P_{max} = K_a (w + 1.2l\gamma) \qquad (10)$$

If there is no surcharge, then the maximum pressure is even simpler.

$$P_{max} = 1.2K_a l\gamma \qquad (11)$$



[FIG. 7] Fairly Constant χ Parameter

COMPARISON OF RESULTS

Experience has shown that soil pressure on lagging is generally constant with depth. Deeper excavations typically do not have thicker lagging; rather the supporting piles have to be larger to resist the greater lateral earth pressures. The model confirms this phenomenon.

The model can be compared with Terzaghi's trap door analogy given by Spencer, White and Prentis, Inc. (1986). According to this analogy, the maximum pressure on lagging is given by

$$P_{\max} = K_a \frac{l\left(\gamma - \frac{2c}{l}\right)}{2\tan\varphi} \qquad (12)$$

which for cohesionless soils reduces to

$$P_{\max} = \frac{K_a l \gamma}{2\tan\varphi} \qquad (13)$$

When Eqn. 13 is compared with the new model, Eqn. 11, one observes that there are many similarities. In fact, both equations result in the same pressure at an angle of internal friction of approximately π/8 (22.5 deg). The trap door analogy predicts much higher pressure (about 155%) at smaller angles of friction. The new model is not influenced as much by friction angle but is becomes more conservative at higher angles of friction.

Using the model, timber lagging thicknesses were calculated for three theoretical soils and compared to the thicknesses recommended in the chart by Goldberg-Zoino and Associates. The competent soil was assumed to have an internal angle of friction of 38 degrees and a unit weight of 1,920 kg/m3 (120 pcf). The difficult soil was assumed to have an angle of internal friction of 28 degrees and a unit weight of 1,760 kg/m3 (110 pcf). The potentially dangerous soil was assumed to have an angle of internal friction of 18 degrees and a unit weight of 1,600 kg/m3 (100 pcf). For the purpose of this comparison, lagging was assumed to have a maximum bending stress of 69 MPa (1,000 psi) which is consistent with the lowest reported values in the FHWA report. NDS (2005) factors for short duration use, wet service, repetitive member, and flat use were incorporated into the design. When combined, these factors increase bending strength by a factor of approximately 1.6.

Shown in Table 1 is a comparison of the recommended thickness from Goldberg-Zoino and the calculated thickness based on the model for the three different soils. It is important to note that the clear span of the lagging shown on the table is defined as the distance between the outermost extents of the H-Pile flanges, not the center-to-center spacing of the piles. The calculated values based on the model are not as conservative as the values shown on the Goldberg-Zoino chart for short free spans and almost exactly the same for longer spans. This seems to match common practice fairly well.

DISCUSSION

The model can be used to determine required lagging thickness for many soil conditions and load cases outside those considered in the Goldberg-Zoino chart. The lower portion of Table 1 shows the required lagging thickness for the same three different soil conditions and lagging spans of 1.52 to 3.05 m (5 to 10 ft) with a 9.58 kPa (200 psf) uniform surcharge at the ground surface. This is an important capability when the soldier pile and lagging wall system borders roads, sidewalks, or other structures.

The model also allows for determination of lateral earth pressures on other lagging materials. For comparison, the model was used to calculate required lagging thicknesses for utility grade lumber. Utility grade lumber is rated at only ¼ times the allowable bending strength of construction grade lumber according to NDS (2005). It is very apparent the effect that timber strength has on the required lagging thickness. On average, utility grade lumber needs to be almost twice as thick as construction grade lumber.

The model also could be used to size other materials such as flexible steel decking

[TABLE 1] Comparison of Results

Surcharge = 0 psf	Lagging Clear Span (ft)						
	5	6	7	8	9	10	
	Recommended Lagging Thickness (in)						
Competent Soils							
φ= 38 deg	*2*	*3*	*3*	*3*	*4*	*4*	*Goldberg-Zoino*
γ= 120 pcf	**1.4**	**1.8**	**2.3**	**2.8**	**3.4**	**4.0**	**Model (F'$_b$=1,600)[1,3]**
Difficult Soils							
φ= 28 deg	*3*	*3*	*3*	*4*	*4*	*5*	*Goldberg-Zoino*
γ= 110 pcf	**1.6**	**2.2**	**2.7**	**3.3**	**4.0**	**4.6**	**Model (F'$_b$=1,600)[1,3]**
Potentially Dangerous Soils							
φ= 18 deg	*3*	*3*	*4*	*5*	-	-	*Goldberg-Zoino*
γ= 100 pcf	**1.9**	**2.6**	**3.2**	**3.9**	**4.7**	**5.5**	**Model (F'$_b$=1,600)[1,3]**

Surcharge = 200 psf	Lagging Clear Span (ft)						
	5	6	7	8	9	10	
	Recommended Lagging Thickness (in)						
Competent Soils							
φ= 38 deg	**3.2**	**4.1**	**5.1**	**6.2**	**7.3**	**8.5**	**Model (F'$_b$=400)[2,3]**
γ= 120 pcf	**1.6**	**2.0**	**2.5**	**3.1**	**3.6**	**4.2**	**Model (F'$_b$=1,600)[1,3]**
Difficult Soils							
φ= 28 deg	**3.8**	**4.8**	**6.0**	**7.2**	**8.6**	**10.0**	**Model (F'$_b$=400)[2,3]**
γ= 110 pcf	**1.9**	**2.4**	**3.0**	**3.6**	**4.3**	**5.0**	**Model (F'$_b$=1,600)[1,3]**
Potentially Dangerous Soils							
φ= 18 deg	**4.5**	**5.8**	**7.2**	**8.7**	**10.2**	**11.9**	**Model (F'$_b$=400)[2,3]**
γ= 100 pcf	**2.2**	**2.9**	**3.6**	**4.3**	**5.1**	**5.9**	**Model (F'$_b$=1,600)[1,3]**

[1] Construction grade mixed hardwood, douglas fir, hem-fir, and spruce species (F_b=1,000).
[2] Utility grade mixed hardwood, douglas fir, hem-fir, and spruce species.
[3] Incorporates wet use factor=1.0, load duration factor=1.15, repetative member factor=1.15, and flat use factor=1.3.

spanning between soldier piles. One caution is that the derivation of the model is based on the assumption that a lagging material that is considerably less rigid than the soldier piles. Rigid pre-cast concrete plank may be required to carry full active earth pressures.

Recently, the model was tested successfully on a project in New York City for an unusual shoring condition. The model was used to estimate the earth pressure on an existing 6-wyth brick foundation wall that was braced with soldier piles. A photograph of the wall system is shown in Fig. 8. The brick wall in the photograph existed directly adjacent a gas station with one-story block structure, several buried tanks, and a canopy. The developer did not have permission to place shoring outside of the brick wall. The shoring contractor determined that there was too much risk of movement of the adjacent structures to remove the brick wall.

It was decided to attempt to use the brick wall as lagging between the soldier piles. Mortar in the brick wall was severely degraded such that it was essentially held together by friction. The soils were silty sands and high plastic silts with some ground water. The punching and flexural strength of the brick wall was estimated based on a “dry stack” approach using friction only. Lateral earth pressures based on the model indicated that the brick wall would bridge between the soldier piles with sufficient factor of safety. The excavation was made without excess movement or any damage to the nearby structures. The brick wall was approximately ten feet deep. The excavation extended to a depth of approximately 5 m (16 ft) below existing grades. Wood lagging was used below the brick wall. A waler with cross braces was positioned near the top of the soldier piles. The waler was removed after construction of the structural mat foundation.

On another recent project, the Convention Center Hotel project in Denver, soil caving occurred during placement of timber lagging. The soil conditions consisted of fairly clean, poorly graded, coarse sand overlying claystone bedrock. The soil which flowed out from beneath the lagging formed a nearly perfect silo shape as shown in Fig. 9. This image gives credence to the assumptions used in development of the model for sand soils. Although this caving occurred, the soil successfully arched between the solder

[FIG. 8] Existing Brick Wall Used as Lagging

that would be determined from Terzaghi's trap door analogy given by Eqn. 12.

Those who have worked around soldier pile and lagging systems for some time have long recognized that cohesive soil behind lagging seldom comes into contact with the lagging. The photograph shown in Fig. 10 taken from another project in Colorado is a demonstration of this. The gap between the cohesive soils and the lagging at the top of the wall system is very apparent. In addition, the lack of any discernable deflection of the lagging is clearly shown despite the fact that the wall is in excess of 5.5 m (18 ft) tall. (Hart, 2008)

piles with no detriment to the shoring system. (Hart, 2008)

Some attempt was made to include cohesion in the derivation of the model so that it could be extended to fine grain soils. It was found during that exercise that a small amount of cohesion significantly reduced the computed pressure on the lagging. In fact, the predicted pressure on the lagging became negligible at a cohesion, c, given by

$$c = \frac{l\gamma}{2} \qquad (14)$$

This indicates that a soil cohesion of only about 14.4 kPa (300 psf) would reduce pressure to zero for lagging with a clear span of 1.52 m (5 ft). Interestingly, this is exactly the same result

[FIG. 9] Soil Silo Formed by Caving (Courtesy of Coggins and Sons, Inc.)

Many fine grain soils and some well-graded coarse grain soils exhibit some cohesion. In some cases, this cohesion is apparent meaning that it can dissipate over time and with the introduction of moisture. The use of cohesion

[FIG. 10] Separation Between Lagging and Cohesive Soils (Courtesy of Coggins and Sons, Inc.)

in the design of temporary shoring systems should be approached with caution and is the decision of the experienced designer.

It was commented by one of the reviewers of this paper that tie-back post tensioning often governs the lateral pressure on lagging for tall walls. This is an excellent observation. It is suggested that the upper limit of lagging pressure in this case could be computed by substituting the passive earth pressure coefficient, K_p, for the active earth pressure coefficient in Eqns. 8 and 11.

CONCLUSIONS

A mathematical model based on a "silo" shaped sliding wedge analysis was presented. The results of the mathematical model compare well with the recommended lagging thicknesses shown in the chart prepared by Goldberg-Zoino and Associates in the 1976 FHWA report. Using the mathematical model produces results which are slightly more conservative than the charted values at larger lagging spans, but the model allows the designer the freedom of designing outside of the normal situations. The model predicts a constant lateral earth pressure beginning at a depth of roughly 1.4 times the spacing between the soldier piles.

Reduced active pressure diagrams suggested previously by others were not compared with the model. The reason is because the reduced active pressure diagrams suggest a lateral pressure that increases without limit, and the new model gives a constant value of pressure beyond a certain depth. Any comparison between the reduced active pressure diagrams and a new model would show one value that matches exactly at some depth. Thereafter, the reduced active pressure diagrams would be more conservative for deeper excavations. A constant pressure model is a better representation of conditions observed in practice.

REFERENCES

1. Macnab, A. (2002) Earth Retention Systems Handbook, McGraw-Hill, New York, pp. 319-322
2. Goldberg, D.T., Jaworski, W.E. and Gordon, M.D. (1976) *"Lateral Support Systems and Underpinning"*, FHWA-RD-75-128, pp 118-121
3. Hart, J. (2008) Coggins and Sons, Inc., Denver, CO (Personal Communication)
4. American Forest and Paper Association, (2005) *"National Design Specification, Design Values for Wood Construction"*, pp 31-35
5. US Navy (1988) *"Military Handbook: Seawalls, Bulkheads, and Quaywalls"* MIL-HDBK-1025/4, Sept. 30
6. Terzaghi, K. (1943) Theoretical Soil Mechanics, Wiley, New York
7. Spencer, White and Prentis, Inc. (1986) "Lagging Design", Sample Calculations provided by Tom Tuozzolo, Moretrench Geotec, Rockaway, NJ (unpublished)
8. Bowles (1988) Foundation Analysis and Design, 4th Edition, McGraw-Hill, Inc., New York