Effective Bearing Length of Crane Mats

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INTRODUCTION

Crane mats are used to distribute the high concentrated loads from mobile cranes over a relatively large ground area so that the soil is loaded at tolerable bearing pressures. This has been common construction industry practice for many decades. Although crane mats are most commonly made of heavy timbers, fabricated steel mats are occasionally used under large cranes or when soil conditions are poor.

The analysis of a crane mat requires a determination of the length of the mat that actually bears on the soil and contributes to the support of the crane. At working loads, this is a relatively simple "beam on an elastic foundation" problem. However, such a solution may not produce a realistic result due to the nonlinearity of the soil as the ultimate bearing capacity is approached. Further, the elastic properties of the soil needed to perform such an analysis are not often available.

The purpose of this paper is to develop a practical means of calculating the effective bearing length of a crane mat that is based on readily available values and that produces an acceptably safe and reliable result.

CURRENT PRACTICE

Engineers in construction presently use a number of different approaches to design crane mats. The two most common of these methods are described here.

Mat Length Based on Soil Bearing Capacity

This crane mat design method is the most straightforward. Once the load from the crane has been calculated, whether an outrigger load or a crawler track pressure, the required crane mat area is calculated by dividing the crane load plus the weight of the mat by the allowable ground bearing pressure. Divide this area by the width of the mat and we have the required effective bearing length. This mat length is then used to calculate bending and shear stresses in the mat, based on the assumption of a uniform pressure equal to the crane load divided by the bearing area acting upward on the bottom of the mat. If the actual stresses are equal to or less than the allowable stresses, the mat is acceptable. This method can be written in equation form as Eqs. 1 through 8. The basic arrangement is illustrated in Fig. 1.

Timber design practice (NDS-2005) allows the calculation of the shear force in a beam subject to a uniformly distributed load at a point located a distance from the face of the support equal to the depth of the beam. The shear force in steel or aluminum beams is calculated at the face of the support. Eqs. 7a and 8a are written for the design of timber crane mats. Eqs. 7b and 8b are written for the design of steel or aluminum mats. The appropriate equations for mats made of other structural materials must be determined based on the applicable design practices for those materials.

$$A_{reqd} = \frac{P+W}{q_a} \tag{1}$$

$$L_{reqd} = \frac{A_{reqd}}{B} \tag{2}$$

$$L_c = \frac{L_{reqd} - C}{2} \tag{3}$$

$$q = \frac{P}{L_{reqd} B} \tag{4}$$

$$M = \frac{(qB) L_c^2}{2} \tag{5}$$

$$f_b = \frac{M}{S} \le F_b \tag{6}$$

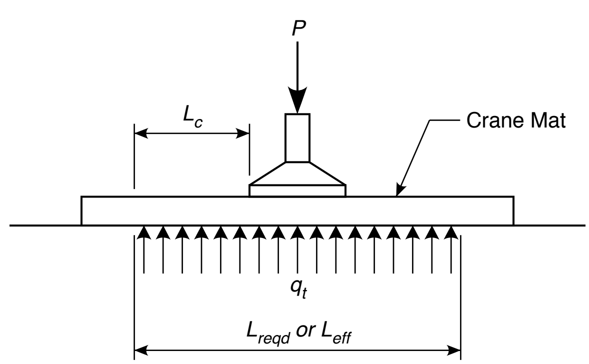

Fig. 1. Simple Crane Mat Arrangement

$$V = (qB)(L_c - d) \tag{7a}$$

$$V = (qB)L_c \tag{7b}$$

$$f_v = \frac{1.5V}{Bd} \le F_v \tag{8a}$$

$$f_v = \frac{V}{n_w d t_w} \le F_v \tag{8b}$$

where:

P	=	crane load applied to one mat;
W	=	self-weight of the mat;
q_a	=	allowable ground bearing pressure;
A_{reqd}	=	required mat bearing area;
B	=	mat width;
L_{reqd}	=	required effective bearing length of the mat;
C	=	bearing width of the track or outrigger pad;
L_c	=	cantilevered length of the mat;
q	=	ground bearing pressure due to P;
M	=	bending moment in the mat;
S	=	section modulus of the mat;
f_b	=	bending stress due to M;
F_b	=	allowable bending stress;
V	=	shear in the mat;
d	=	mat depth (or thickness);
f_v	=	shear stress due to V;
F_v	=	allowable shear stress;
n_w	=	number of webs (steel or aluminum design); and,
t_w	=	web thickness.

Mat Length Based on Mat Strength

This method is the reverse of the first method. Here, the effective bearing length L_{eff} of the mat is assumed initially and is then adjusted until the resulting bending stress or shear stress reaches the corresponding allowable stress. The ground bearing pressure is then computed using this effective bearing length. If the actual pressure is equal to or less than the allowable ground bearing pressure, the mat is acceptable. Again, we can write the method in equation form. As above, Eqs. 13a and 14a are written for the design of timber crane mats and Eqs. 13b and 14b are written for the design of steel or aluminum mats.

$$L_c = \frac{L_{eff} - C}{2} \tag{9}$$

$$q = \frac{P}{L_{eff} B} \tag{10}$$

$$M = \frac{(qB)L_c^2}{2} \tag{11}$$

$$f_b = \frac{M}{S} = F_b \tag{12}$$

$$V = (qB)(L_c - d) \tag{13a}$$

$$V = (qB)L_c \tag{13b}$$

$$f_v = \frac{1.5V}{Bd} = F_v \tag{14a}$$

$$f_v = \frac{V}{n_w d t_w} = F_v \tag{14b}$$

$$q_t = \frac{P + W}{L_{eff} B} \le q_a \tag{15}$$

where:

L_{eff}	=	effective mat bearing length;
q_t	=	actual ground bearing pressure; and,
		all other terms are as previously defined.

Note that this method is iterative. A value of L_{eff} must be assumed, Eqs. 9 through 14 solved, and then L_{eff} adjusted as necessary to satisfy the equalities of Eqs. 12 and 14. Note that the design is complete when either the bending stress or the shear stress reaches its allowable value. When the mat is made of the most common hardwood species and the allowable ground bearing pressure is not unusually high, bending strength usually governs the mat design. However, both shear and bending must always be checked.

Comments on These Design Methods

Both of these crane mat design methods are in popular use and give adequate results. However, there is one important shortcoming in the way these calculations are commonly applied in practice. Neither shows how close a particular design is to reaching its load carrying limit. The first method loads the soil to its allowable bearing capacity and then shows that the stresses in the mats are something less than their allowable values. The second method loads the mats to the allowable bending or shear capacity and then shows that the ground bearing pressure is something less than the allowable pressure.

We can examine this problem by way of an example. Consider a load of 100,000 pounds applied to a mat by an outrigger pad that is 24 inches wide along the length of the mat. This pad is supported at the middle of a 12" x 4' x 20' timber crane mat. The allowable ground bearing pressure for the site is 3,000 psf. Allowable stresses for the mat design are F_b = 1,400 psi and F_v = 200 psi. The mat is checked by both methods in Table 1.

Table 1. Design Method Comparison - Example 1		
	Soil Bearing Capacity Method	Mat Strength Method
Mat Weight, W	4,000 lbs	4,000 lbs
A_{reqd} (Eq. 1)	34.67 ft^2	
L_{reqd} (Eq. 2)	8.67 feet	
L_c (Eq. 3)	3.33 feet	
Assumed L_{eff}		14.48 feet
L_c (Eq. 9)		6.24 feet
q (Eq. 4; Eq. 10)	2,885 psf	1,727 psf
M (Eq. 5; Eq. 11)	769,231 lb-in	1,612,800 lb-in
f_b (Eq. 6; Eq. 12)	668 psi	1,400 psi
V (Eq. 7a; Eq. 13a)	26,923 lbs	36,184 lbs
f_v (Eq. 8a; Eq. 14a)	70 psi	94 psi
q_t (Eq. 15)	3,000 psf	1,796 psf

Both methods show that the mat design is acceptable, but the design margin is not obvious. The Soil Bearing Capacity method shows that the applied ground bearing pressure is equal to the allowable bearing pressure, the mat bending stress is 668 psi, or 48% of the allowable bending stress, and the mat shear stress is 70 psi, or 35% of the allowable shear stress. The Mat Strength method shows that the mat is loaded to its allowable bending stress and 47% of the allowable shear stress and that the ground bearing pressure is 1,796 psf, or 60% of the allowable bearing capacity.

Now let's repeat this analysis using a load of 135,256 pounds and both crane mat design methods. All other values remain the same. The results of this exercise are shown in Table 2.

Here we see that the two mat design methods converge at the load where both the mat strength and the soil bearing capacity limits are reached. This second example shows us that the capacity limit of this mat on this soil is a crane load of 135,256 pounds. The mat capacity is limited by its bending strength. Thus, the crane load of 100,000 pounds in the first example loaded the mat/soil combination to 74% of its capacity. This cannot be seen in the calculations summarized in Table 1. Although these commonly used crane mat design methods generally yield results that are acceptably safe, they do not provide an indication of the percent utilization (or demand/capacity ratio) of the mat/soil combination. As such an expression of calculation results is often desirable, a different design method is proposed.

Table 2. Design Method Comparison - Example 2		
	Soil Bearing Capacity Method	Mat Strength Method
Mat Weight, W	4,000 lbs	4,000 lbs
A_{reqd} (Eq. 1)	46.42 ft^2	
L_{reqd} (Eq. 2)	11.60 feet	
L_c (Eq. 3)	4.80 feet	
Assumed L_{eff}		11.60 feet
L_c (Eq. 9)		4.80 feet
q (Eq. 4; Eq. 10)	2,914 psf	2,914 psf
M (Eq. 5; Eq. 11)	1,612,800 lb-in	1,612,800 lb-in
f_b (Eq. 6; Eq. 12)	1,400 psi	1,400 psi
V (Eq. 7a; Eq. 13a)	44,317 lbs	44,317 lbs
f_v (Eq. 8a; Eq. 14a)	115 psi	115 psi
q_t (Eq. 15)	3,000 psf	3,000 psf

MAT EFFECTIVE BEARING LENGTH CALCULATION

A practical method of crane mat design can be derived that is based upon the accepted current practice, but that gives an indication of the utilization of the mat strength and the soil bearing capacity. This method uses as input only values that are routinely available.

Effective Length Calculation Method

Consider first the bending strength of the mat. We wish to determine the effective bearing length L_{eff} at which both the allowable bending strength of the mat and the allowable ground bearing pressure of the soil are reached. This can be done by expressing q in terms of q_a (Eq. 16) and then writing Eq. 11 in terms of this expression for q, Eq. 9, and the allowable moment of the mat M_n (Eq. 17), where $M_n = F_b S$. By rearranging terms, Eq. 17 can be written as Eq. 18. The last term of this equation can be shown to be trivial, so Eq. 18 reduces to Eq. 19, which is a quadratic equation in which the quantity in the first set of parentheses is a, the quantity in the second set is b, and the quantity in the third set is c. The standard solution is shown in Eq. 20.

$$q = q_a - \frac{W}{L_{eff} B} \tag{16}$$

$$M_n = \left(q_a - \frac{W}{L_{eff} B} \right) \frac{B}{2} \left(\frac{L_{eff} - C}{2} \right)^2 \tag{17}$$

$$\left(q_a B\right) L_{eff}^2 + \left(-2q_a BC - W\right) L_{eff} + \left(q_a BC^2 + 2CW - 8M_n\right) - \frac{C^2 W}{L_{eff}} = 0 \qquad (18)$$

$$\left(q_a B\right) L_{eff}^2 + \left(-2q_a BC - W\right) L_{eff} + \left(q_a BC^2 + 2CW - 8M_n\right) = 0 \qquad (19)$$

$$L_{eff} = \frac{-b \pm \sqrt{b^2 - 4ac}}{2a} \le L \qquad (20)$$

where L is the actual length of the mat.

A solution of L_{eff} must also be made based on the shear strength of the crane mat. Eqs. 21 and 22 are based on timber design practice. Here, Eq. 13a is written in terms of Eqs. 9 and 16 and the allowable shear strength of the mat V_n (Eq. 21), where $V_n = F_v Bd/1.5$. This equation is then rewritten in quadratic form (Eq. 22) where the quantity in the first set of parentheses is a, the quantity in the second set is b, and the quantity in the third set is c. Eq. 20 is used to solve for L_{eff}.

$$V_n = \left(q_a - \frac{W}{L_{eff} B}\right) B \left(\frac{L_{eff} - C}{2} - d\right) \qquad (21)$$

$$\left(q_a B\right) L_{eff}^2 + \left(-2V_n - q_a BC - 2q_a Bd - W\right) L_{eff} + \left(WC + 2Wd\right) = 0 \qquad (22)$$

When designing mats made of steel or aluminum, the shear strength is evaluated at the point of maximum shear, rather than at a distance d from that point. Thus, Eqs. 13b, 21, and 22 are written for steel or aluminum design as Eqs. 23, 24, and 25, where $V_n = F_v n_w d t_w$.

$$V = \left(qB\right) L_c \qquad (23)$$

$$V_n = \left(q_a - \frac{W}{L_{eff} B}\right) B \left(\frac{L_{eff} - C}{2}\right) \qquad (24)$$

$$\left(q_a B\right) L_{eff}^2 + \left(-2V_n - q_a BC - W\right) L_{eff} + WC = 0 \qquad (25)$$

Last, a limit of the effective bearing length based on deflection is proposed. Examination of numerous design examples using only the criteria of bending and shear strength shows that some mats exhibit excessive deflections (greater than one inch) on softer soils. Therefore, we should limit the effective bearing length based on the stiffness of the mats. This is a more difficult criterion to define, since there isn't a well defined deflection limit state as exist for bending and shear. A deflection limit of 0.75% of L_c is suggested, based on an examination of numerous mat designs.

The deflection of a crane mat is commonly calculated by treating the mat as a cantilever beam of length L_c and loaded by an upward uniform pressure equal to q. We can express this in equation form as Eq. 26.

$$\Delta = \frac{\left(qB\right) L_c^4}{8EI} \qquad (26)$$

where:

Δ	=	vertical deflection;
E	=	modulus of elasticity;
I	=	moment of inertia of the mat; and,
		all other terms are as previously defined.

This deflection criterion will only control the effective bearing length with softer soils. Examination of such designs shows us that $q \approx 0.9\ q_a$. If we let $\Delta = 0.0075\ L_c$ and use this approximation for q, we can easily solve Eq. 26 for L_c (Eq. 27) and L_{eff} (Eq. 28).

$$L_c = \sqrt[3]{\frac{0.06EI}{0.9\left(q_a B\right)}} \qquad (27)$$

$$L_{eff} = 2L_c + C \le L \qquad (28)$$

The smallest value of L_{eff} based on the moment and shear strength analyses and the deflection analysis is taken as the effective bearing length of the crane mat. The mat and the soil are then evaluated based on the usual assumption of a uniform bearing pressure q (Eq. 10) between the mat and the soil over the effective bearing area.

The performance of this design method can be examined by sizing a crane mat using the method and then performing a failure analysis to determine the actual capacity provided. Consider a standard 12" x 4' x 20' hardwood timber crane mat centrally loaded by a 24" wide pad. The applied load is 175,000 pounds. The ultimate bearing capacity of the soil is 10,000 psf and a factor of safety of 2.00 is to be applied, giving us an allowable ground bearing pressure of 5,000 psf. As before, the allowable stresses for the mat design are 1,400 psi in bending and 200 psi in shear. The results of the mat design are shown in Table 3.

The mat behavior may be treated as elastic for our purposes. Soil may be treated as elastic at allowable load levels, but is very nonlinear as the ultimate bearing capacity is approached. Thus, we will use two different analysis methods to evaluate this design.

The mat behavior at the working load can be analyzed as a beam on an elastic foundation (Young, et al, 2012). In

Table 3. Example Mat Design Results		
Mat Weight, W	4,000 lbs	
L_{eff} (Eq. 19)	9.41 feet	controlling value
L_{eff} (Eq. 22)	11.81 feet	
L_{eff} (Eq. 26)	13.54 feet	
L_c (Eq. 9)	3.70 feet	
q (Eq. 10)	4,652 psf	
M (Eq. 5)	1,530,575 lb-in	
f_b (Eq. 6)	1,329 psi	95% of F_b
V (Eq. 7a)	50,288 lbs	
f_v (Eq. 8a)	131 psi	65% of F_v
q_t (Eq. 15)	4,758 psf	95% of q_a

addition to the values already discussed, we must also know the modulus of elasticity E of the timbers and the modulus of subgrade reaction k_s of the soil. E may be taken as 1,200,000 psi for the hardwood species commonly used for crane mat construction. Bowles (1996) suggests that a practical value of k_s in kips per cubic foot is 12 q_{ult} where q_{ult} is the ultimate bearing capacity in kips per square foot. Alternately, k_s in pounds per cubic inch is q_{ult} / 144 where q_{ult} is the ultimate bearing capacity in pounds per square foot. The basis of this approximation is illustrated in Fig. 2.

Using these values, the results of the beam on an elastic foundation analysis are shown graphically in Fig. 3. We see that the actual bearing pressure between the mat and the soil is greatly variable, not uniform as assumed in the standard design methods. However, the peak bearing pressure due to P is only about 5% greater than that given by the proposed

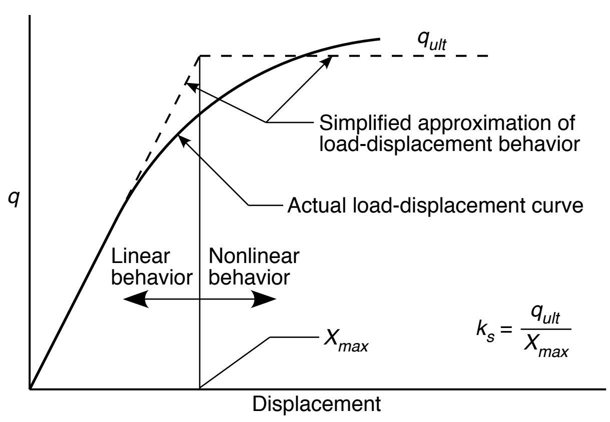

Fig. 2. Modulus of Subgrade Reaction (based on Bowles 1996, Fig. 9-9)

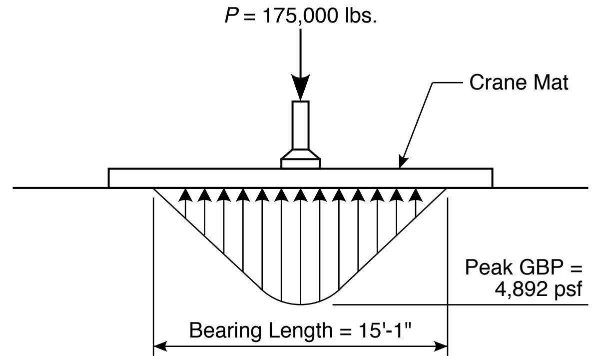

Fig. 3. Bearing Pressure Curve at the Design Load

design method, which is not significant. The actual bearing length is shown as 15'-1", markedly greater than the effective bearing length of 9'-5" calculated using this design method.

For the failure analysis, we can use the program FADBEMLP, a nonlinear analysis program that is packaged with the Bowles (1996) text. This program treats the beam as elastic and the soil as elastic/perfectly plastic (Fig. 2). That is, the soil behavior is linearly elastic up to the ultimate bearing capacity and then perfectly plastic thereafter. The value of k_s = 12 q_{ult} discussed above is based on the assumption that the ultimate bearing capacity is reached at a deformation of about one inch. As the bearing pressure in the center of the mat reaches q_{ult}, the bearing pressure curve takes on the shape shown in Fig. 4, for which the applied load is 460,000 pounds, about 2.6 times the design load of 175,000 pounds.

We can see from the shape of the pressure curve that the soil still has additional support capability at this load. The moment in the mat at this load is 5,685,360 pound-inches, which gives a bending stress of 4,935 psi. This indicates that the mat will likely fail before the ultimate bearing capacity of the soil is reached.

If we look at the mat/soil behavior at 350,000 pounds, twice the design load, we find that the soil is still in the elastic range. At this load, the peak soil bearing pressure is 9,783 psf

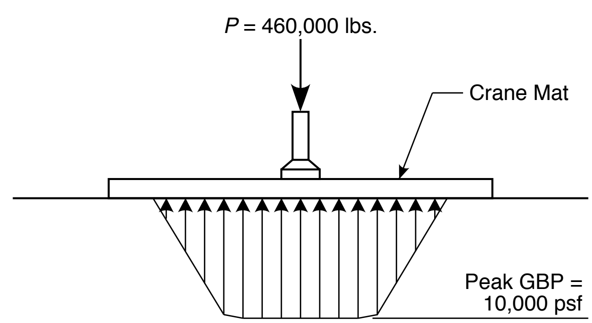

Fig. 4. Bearing Pressure Curve at 460,000 pounds

and the moment in the mat is 3,660,397 pound-inches, which gives a bending stress of 3,177 psi, or 227% of the allowable bending stress. The allowable bending and shear stresses for hardwood timbers are based on a nominal design factor of 2.1 or greater (ASTM 2000, ASTM 2006), so we can see that the proposed method provides a strength design factor on the order of 1.75 for this example.

Given the soil conditions on many construction sites, the use of the approximation for the modulus of subgrade reaction discussed here is questionable. Excavated and backfilled areas, compacted surface layers, and other deviations from a homogeneous soil mass all serve to increase the uncertainty with which soil elastic properties can be determined. Analyses such as those done here for reference are usually not practical since the needed soil elastic property, the modulus of subgrade reaction, is generally not known reliably. Thus, although the tools are available to perform such an analysis, the questionable input renders the results similarly questionable.

Comments on Support Deflection

The deflection calculation discussed in the preceding section provides some insight into the behavior of the mat, but is not an accurate calculation of the mat/soil deformation under load. This is due to the use of the idealized values of q and L_c in Eq. 26. More likely deflections can be investigated using the beam on an elastic foundation approach with the approximate value of k_s previously discussed.

Analyses of dozens of mat/soil combinations with crane loads set equal to the maximum value permitted by the design method proposed here show that the actual displacement of the mat will differ, sometimes significantly, from that computed using Eq. 26. However, the calculated elastic displacements do not vary much as a group.

This study examined 12" thick by 4' wide timber mats of oak, Mora and Emtek™, one or two layers thick, supported on soil with q_{ult} varying from 2,000 psf to 16,000 psf. The elastic analysis deformations differed from the values calculated using Eq. 26. The greatest differences occurred at the lowest values from Eq. 26. However, all of the elastic analysis deformations for this group of mat/soil combinations were in the range of about 1/2" to just over 3/4". This indicates that the mat deflections calculated using Eq. 26 are not a true indicator of the mat behavior, but that the method developed here will provide reasonable and consistent support to the crane.

This study also examined the structural design factor provided by the proposed method. The actual design factor was found to vary significantly, with a greater bending strength design factor in the mats occurring in conjunction with the lower allowable ground bearing capacities. The example discussed above noted a design factor of about 1.75. This value was found to be at the low end of the design factor range observed in the study. However, given this reasonable lower bound strength design factor and the consistently small vertical deflections of the mats under operating loads, the calculation method defined here is shown to be practical for most crane mat design applications.

Foundation Stiffness

A guide related to relative stiffness of the mat to the soil is the value of λL_{eff} as defined in Eq. 29 (Bowles 1996), used to distinguish between a rigid and a flexible foundation.

$$\lambda L_{eff} = \sqrt[4]{\frac{k_s B L_{eff}^4}{4EI}} \tag{29}$$

The mat is considered to be a rigid foundation for values of λL_{eff} less than $\pi/4 = 0.79$ and a flexible foundation for values of λL_{eff} greater than $\pi = 3.14$. The mat example of Table 3 gives us a value of λL_{eff} equal to 2.01. Examination of a range of mat design problems using q_{ult} from 2,000 psf to 16,000 psf generally shows values of λL_{eff} in the range of 1.9 to 2.7 for a single layer of conventional hardwood mats or 2.7 to 3.2 for a single layer of high strength (e.g., Emtek™) timber mats. The lower values of λL_{eff} occur at the higher values of q_{ult}.

This calculation of λL_{eff} should be considered as a guide only when exercising engineering judgment in the solution of a crane mat design problem. The value of λL_{eff} is not to be used as a design criterion due to the uncertainty with which k_s is known.

Notes on Practical Application

The purpose of this paper is the derivation of a practical means of calculating the effective bearing length of a crane mat. A few comments are offered here with respect to the application of this material to the design of crane installations.

Calculation of the crane loads to be supported must be done with reasonable accuracy. Many crane manufacturers now provide computer programs that compute the support loads for their products for a given lift configuration. These tools should be used wherever possible.

When sizing mats for an outrigger-supported crane, consideration must be given to the size of the outrigger pad. For example, an 18" diameter pad will bear on only two timbers of a mat made up of 12" x 12" timbers and the tie rods that hold the mat together are not necessarily capable of distributing this concentrated load to the other timbers. In such a case, the mat should be checked considering only the two timbers on which the pad bears. Alternately, a steel plate or timbers placed crosswise can be used to distribute the outrigger load to all of the mat timbers.

The allowable stresses for timber design are taken as 1,400 psi for bending and 200 psi for shear in the example problems. These are practical values for mats made of the types of hardwoods popularly used in the U.S. for crane mat construction. However, the actual allowable stresses used must be appropriate for the species and condition of the timbers under consideration.

Last, the allowable ground bearing pressure q_a for the site must be determined by a qualified engineer. Values of q_a used for the design of foundations for permanent structures are often based on a factor of safety of at least 3.00. Support of a mobile crane does not require consideration of long-term settlements and many of the uncertainties associated with the design of permanent structures do not exist for a crane installation. Thus, a lower factor of safety for q_a may be appropriate. A value of 2.00 was used in the example problems.

CONCLUSION

This paper presents a practical method for calculating the effective bearing length of a crane mat that is loaded by a single outrigger or crawler track. The principles upon which this derivation is based can be used to expand this approach to the design of a crane mat supporting two loads.

The true behavior of the mat/soil combination is more complex than is implied by the standard calculation approach. A more theoretically "exact" approach is usually not practical due to the difficulty in determining the elastic properties of the soil. As a result, it is sometimes necessary to apply engineering judgment in the solution of a crane support design problem. Because of this potential need, it is necessary that users of this material possess the engineering background and practical experience required to exercise this judgment.

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ABOUT THIS REVISION

This paper was first presented at the 2010 Crane & Rigging Conference. Readers of the paper raised questions that indicated that the paper lacked clarity in some areas, thus impairing its usefulness to the industry. This update, completed in 2012, includes minor additions and revisions to improve its clarity. Of particular significance are the shear strength equations added to distinguish between timber mat design and steel or aluminum mat design. In general, however, the substance of the paper in terms of its scope and technical content has not been changed.

SI CONVERSION FACTORS

Following are conversion relationships between USCU and SI for the quantities used in this paper. The standard abbreviations for the SI units are shown in parentheses.

1 inch	=	25.4 millimeters (mm)
1 foot	=	0.304 800 meter (m)
1 pound	=	0.453 592 kilogram (kg)
1 pound	=	4.448 222 newtons (N)
1 short ton	=	0.907 185 metric ton (tonne) (t)
1 short ton	=	8.896 444 kilonewtons (kN)
1 square inch	=	0.000 645 square meter (m^2)
1 square foot	=	0.092 903 square meter (m^2)
1 pound-inch	=	0.112 985 newton-meter (N-m)
1 pound-foot	=	1.355 818 newton-meters (N-m)
1 pound per square inch	=	6.894 757 kilopascals (kPa)
1 pound per square foot	=	47.880 260 pascals (Pa)
1 pound per cubic inch	=	271.447 161 kilonewtons per cubic meter (kN/m^3)
1 kip per cubic foot	=	157.087 459 kilonewtons per cubic meter (kN/m^3)