Automatic Design Algorithm for the Tower Crane Foundations

Sungho Lee, Goonjae Lee, Chaeyeon Lim, and Sunkuk Kim

Abstract—Foundation of tower crane serves to ensure stability against vertical and horizontal forces. If foundation stress is not sufficient, tower crane may be subject to overturning, shearing or foundation settlement. Therefore, engineering review of stable support is a highly critical part of foundation design. However, there are not many professionals who can conduct engineering review of tower crane foundation and, if any, they have information only on a small number of cranes in which they have hands-on experience. It is also customary to rely on empirical knowledge and tower crane renter's recommendations rather than designing foundation on the basis of engineering knowledge. Therefore, a foundation design automation system considering not only lifting conditions but also overturning risk, shearing and vertical force may facilitate production of foolproof foundation design for experts and enable even non-experts to utilize professional knowledge that only experts can access now. This study proposes Automatic Design Algorithm for the Tower Crane Foundations considering load and horizontal force.

Keywords—Tower Crane, Automatic Design, Foundations, Optimization Algorithm, Stability

I. INTRODUCTION

IN case of high-rise building construction project located in densely populated urban area, tower crane cannot lift load at free standing height alone but beyond applicable building height. Tower crane lifting load to high elevation is exposed to horizontal force created by natural phenomenon such as typhoon or gust or incident caused by its self-weight or lifting load. For example, when the typhoon Maemee struck Korea in 2003, 43 tower cranes capsized or collapsed, taking gigantic toll in terms of loss of life and damage to properties (Koo 2006)[1]. In 2006, alone, 6 tower cranes collapsed (KOSHA 2007)[2]. In the U.S., between 1991 to 2002, crane-related fatalities were found out to account for 8% of total construction fatalities (Beavers et al., 2006)[3]. Stability of tower crane is basically determined by required lifting load and crane type selection as per construction conditions. To be more specific, it is determined by jib length, lateral support and foundation, etc. Among them, tower crane foundation serves to ensure stability against vertical and horizontal forces. If foundation stress is not sufficient, tower crane may be subject to overturning, shearing or foundation settlement. Therefore, engineering review of

stable support is a highly critical part of foundation design.However, there are not many professionals who can conduct engineering review of tower crane foundation and, if any, they have information only on a small number of cranes in which they have hands-on experience. It is also customary to rely on empirical knowledge and tower crane renter's recommendations rather than designing foundation on the basis of engineering knowledge. Therefore, a foundation design automation system considering not only lifting conditions but also overturning risk, shearing and vertical force may facilitate production of foolproof foundation design for experts and enable even non-experts to utilize professional knowledge that only experts can access now. There have been several studies focusing on the review of base plate stability following selection of tower crane type [4, 5, 6], however, such studies go only as far as conducting simply structural review, as base plate design and construction is largely tied to standard drawings furnished by tower crane manufacturers, which leads researchers to overlook other factors [7]. There was also a study to optimize base plate size on the basis of the stability and cost-effectiveness of tower crane [7], however, such study also revealed some difference from this study focusing on automation of base plate and pile design in terms of scope and method.

This study aims to develop automatic design algorithm for the tower crane foundations. Foundations herein include base plate and pile and stability review targets overturning moment, bearing force of soil, shearing and pile bearing capacity. This study, to present automatic design of foundations, examined preceding studies including base plate sizing process, analyzed stability review items and proposed automatic foundation design algorithm on the basis of analysis outcomes. Automatic design algorithm analyzes overturning moment, bearing force of soil, shearing, and pile bearing capacity in consideration of site conditions and tower crane selection and designs footing bar arrangement, pile quantity, and spacing automatically to ensure stability.

II. THEORETICAL SURVEY

A. Literature survey

Leonhard [8] et al. studied safety and efficiency of lifting equipment operation along with many others. Leonhard introduced Intelligent Technology for Mobile Crane Monitoring System in 1997 [8]. John proposed video communication system to improve productivity and safety of crane operation [9] and Leung studied development of lifting time estimation model for tower crane in 1999 [10]. Such studies as focused on lifting plan and lifting equipment

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World Academy of Science, Engineering and Technology
International Journal of Civil and Environmental Engineering
Vol:5, No:12, 2011

operation aimed to improve efficiency in planning and operation phases and reduce safety incidents during equipment operation, which is different from the objectives hereof.Several researchers also studies crane selection in connection with lifting plan. Furusaka and Gray (1984) proposed a method to select optimum crane by using objective function that could minimize the total cost of the hire, assembly and dismantling [11]. Gray and Little (1985) suggested a systematic approach to select mobile and tower crane suitable for design work during the early design process. Notably, in case of tower crane, they presented a systematic approach implemented by a computer-based expert system that could design not only luffing jib and saddle jib but also select and locate crane base out of various alternatives in consideration of site conditions [12]. However, they neither proposed a method to review stability of crane following selection nor an approach to utilizing information already in place for various available crane types.Following studies have focused intensively on stability review in relation to tower crane installation. First, Hoh, Jong-Gwan et al. (2007)[13] proposed a tower crane stability simulation program to improve efficiency of stability review following tower crane type selection and Hoh, Jong-Gwan et al. (2007)[14] developed a system to optimize tower crane selection to site conditions and review its stability in lifting planning stage. Han, Gap-Kyoo et al.(2007)[15] introduced an approach to reviewing base plate stability using opti-crane program following crane type selection and Hoh, Jong-Gwan (2008)[16] studied needs for tower crane stability review tool and development program after examining tower crane operation status in Korea. Such studies related to stability review and system implementation, failing to propose automatic foundation design algorithm. Therefore, this study aims to propose stability review approach that can enable automatic foundation design and present necessary algorithm.

B. Foundation and piles of tower crane

Foundation of tower crane includes fixing anchor and concrete locking it in place. Foundation of fixed base tower crane included in the scope hereof is installed by locking fixing angle in concrete block on the ground and used mostly for reinforced concrete apartment building and low structure. As mentioned in the scope of study, it can be used when the bearing force of soil is sufficient and the strength of concrete block for fixing anchor must be 255kg/cm^2 or more. [7].

III. STABILITY REVIEW OF TOWER CRANE FOUNDATIONS

A. Stability review of foundation

To develop an auto foundation design algorithm, tower crane base plate structure needs to be reviewed, using maximum tower crane free standing height and corresponding load. As a structural review, overturning moment which means moment caused by external force and intended to tilt or tip over a structure beyond its equilibrium is reviewed. And the bearing force of soil where tower crane is installed is reviewed to see if it can bear the load of tower crane and base plate. Lastly, one

way shear and two way shear are reviewed in consideration of design shear strength of concrete against the self weight of tower crane installed on tower crane base plate.To review the overturning risk of tower crane by load eccentricity, overturning moment(M_o) that can overturn the foundation by moment applied to tower crane (M) and horizontal force (H) is estimated and resistance moment(M_r) that can resist self weight of tower crane foundation(W) and vertical force(V) is calculated. It is deemed to be safe if the ratio between overturning moment and resistance moment is equal to or greater than safety factor (n) 1.5 as calculated by (1) to (3)

$$M_o = M + (H \times D) \tag{1}$$

$$M_r = (W + V) \times \frac{L_{MIN}}{2} \tag{2}$$

$$\frac{M_r}{M_o} \geq (n = 1.5) \ \ OK \tag{3}$$

$Where,$ M_o = Overturing moment

M_r = Resistance moment

M = Momem against tower moment

H = Horizonrall load applied to tower creane

W = Self weight of tower crane base plate

V = Vertical load of tower crane

When the maximum ground pressure exceeds the bearing force of soil, base plate is settled, which can result in the overturning of tower crane. Therefore, risk associated with the bearing force of soil is reviewed. Allowable bearing force of soil was based on the soil bearing force test results or of soil or N value shown in soil boring log. Maximum ground force is compared to allowable bearing force of soil to determine stability.

To review one way shear and two way shear, required shear strength of tower crane base plate at critical section against x axis and y axis is estimated and compared with design shear strength to determine stability. To calculate design shear strength applied to concrete base plate, in case of one way shear, (4) is used in case of a member under only shear force and bending moment and (5) is used in case of a member under compressive force in axis direction. In case of two way shear, lesser value calculated in (6) is used.

$$V_C = \frac{1}{6} \sqrt{f_{ck}} \cdot b_w \cdot d \tag{4}$$

$$V_C = \frac{1}{6} (1 + \frac{N_u}{14A_o}) \sqrt{f_{ck}} \cdot b_w \cdot d \tag{5}$$

World Academy of Science, Engineering and Technology
International Journal of Civil and Environmental Engineering
Vol:5, No:12, 2011

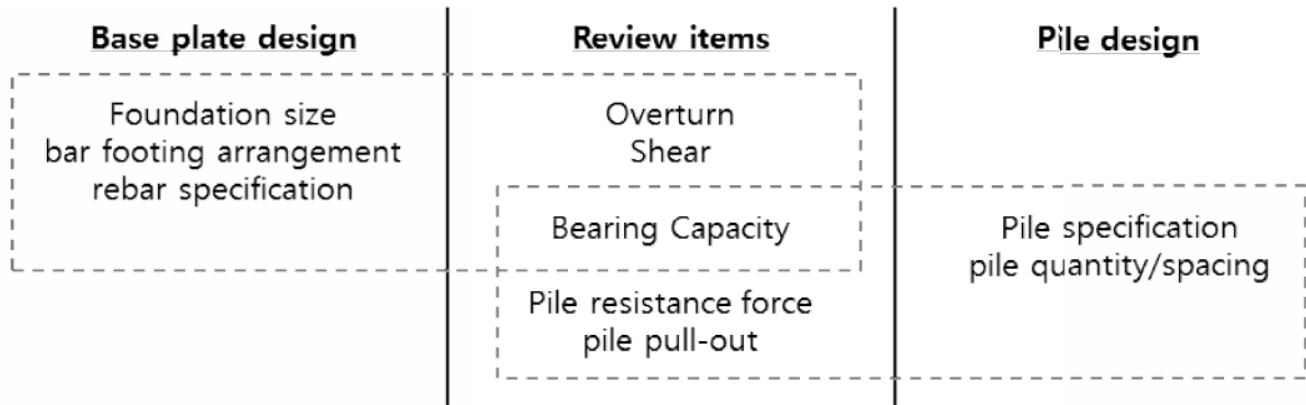Fig. 1 Tower crane foundation stability review items

$$V_C = \frac{1}{6}(1 + \frac{2}{\beta_c})\sqrt{f_{ck}} \cdot b_0 \cdot d$$

$$V_C = \frac{1}{6}(1 + \frac{a_s \cdot d}{2\beta_c})\sqrt{f_{ck}} \cdot b_0 \cdot d$$

$$V_C = \frac{1}{3}\sqrt{f_{ck}} \cdot b_0 \cdot d \qquad \text{the minimum value} \qquad (6)$$

B. Stability review of foundation with piles

If the ground is soft, not suitable for independent footing design or there is rock bed at close location underground, it may be cost-effective and stable to use piles in designing tower crane base plate. Pile foundation used by tower crane distributes the load of tower crane shorn by pile and support shear force and moment caused by reaction of the pile. Pile foundation was also reviewed in terms of one way shear and two way shear as in the case of independent footing and punching shear of the pile itself was reviewed. In addition, pile size and allowable bearing capacity were reviewed against load shorn by tower crane was reviewed.

Overturning review was conducted as in the case of independent footing and overturning moment from pile installation was found to be insignificant. As the load of tower crane and base plate is supported by the bearing capacity of foundation, the number of piles was calculated in consideration of allowable bearing capacity of a single pile. In addition, reaction to be borne by each pile against maximum ground force was calculated and compared with allowable reaction of individual pile to determine stability.

IV. AUTOMATIC DESIGN ALGORITHM OF FOUNDATIONS

A. Concept of automatic foundations design

As described in Section 3, tower crane foundation needs to be designed by reviewing stability against overturn, shear, bearing capacity, pile reaction and pile pull-out. Different roles and stability review items are expected of plate and piles consisting of foundations. First, base plate transfers the load of tower crane to the ground and prevents mast from overturning under horizontal force. Therefore, as Fig. 1 shows, in case of base plate, bearing force of soil, stability against overturning and shearing needs to be reviewed. Next, piles are added if

bearing force of soil is not sufficient and expected to prevent foundation from settlement. Then, bearing capacity, pile reaction and pile pull-out stability needs to be reviewed to determine pile specification, quantity and spacing. Bearing force of soil and shear stress of tower crane can be secured by adjusting the size of base plate. However, if the bearing force of soil on site is less than standard requirement, stability cannot be secured by increasing the size of base plate alone. In such case, pile needs to be added to foundation in order to secure bearing force of soil. Therefore, tower crane foundation is planned in two steps as shown in Fig. 2: base plate design and pile design afterwards, subject to stability review results. A in Fig. 2 shows a step in which base plate bearing capacity, shear and overturn are reviewed and it needs to be determined whether to size up base plate or add piles. If pile addition is required, piles are designed and stability is determined by reviewing bearing capacity, If stability is not secured, pile design needs to be adjusted.The algorithm proposed herein is configured to automate the process of determining base plate size, rebar amount and pile addition and pile quantity. It is also configured to review required stability items in each step automatically as well. The algorithm improves the efficiency and accuracy of foundation design by reducing margin of error as engineers enter a variety of metrics directly and adjust them in several steps.

B. Automatic foundation design algorithm

The algorithm proposed herein is a base plate design algorithm that can be used when tower crane has been selected. As tower crane is selected in consideration of lifting load and working radius, lifting load and free standing height can be imported from tower crane information selected in base plate design step as design metrics. As shown in Fig. 3, once tower crane is selected, base plate is designed from tower crane information and base plate design standards and rebar specification and arrangement spacing are determined.

Then, rebar specification and arrangement spacing are determined on the basis of RC design information and minimum rebar amount is applied first to prevent excessive rebar design.

Next, stability is reviewed rebar arrangement need to be adjusted.

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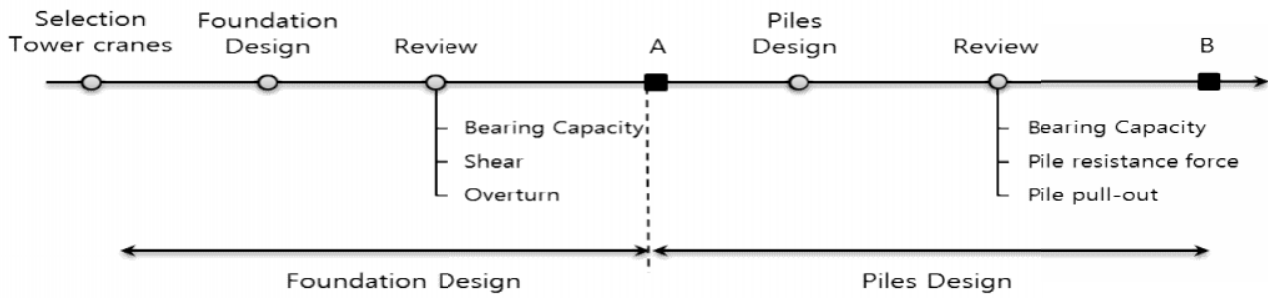Vol:5, No:12, 2011

Fig. 2 Concept of design of foundations

Such steps are repeated until overturn and shear stability is secured. Then, bearing force of soil is reviewed to determine whether or not to install piles. If site conditions limit the size of base plate, making it impossible to secure bearing force of soil, or base plate needs to be too big in order to bearing force of soil, efficiency and cost-effectiveness is compromised. In such case, efficient foundation design that restricts the size of base plate and adds piles is required. Pile specification and quantity are adjusted to secure bearing capacity. When pile design is developed, pile spacing, reaction and pull-out needs to be reviewed in relation to base plate size. Once design is completed, bearing capacity is reviewed again. Foundation design of which stability has been confirmed in such steps is stored and printed out.
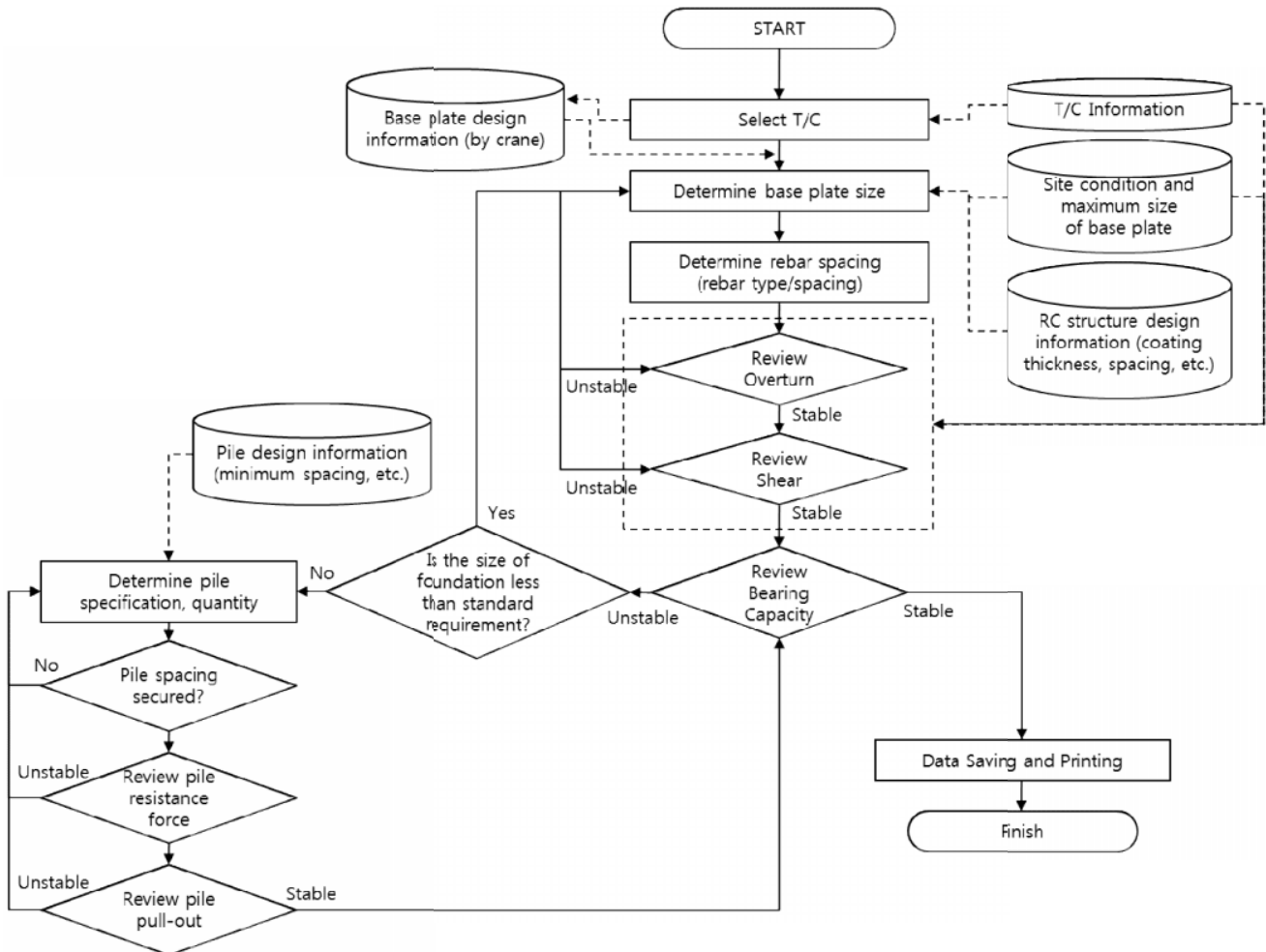

Fig. 3 Automatic design algorithm for the tower carne foundations

V. CONCLUSIONS

Foundation of tower crane serves to ensure stability against vertical and horizontal forces. If foundation stress is not sufficient, tower crane may be subject to overturning, shearing or foundation settlement. Therefore, engineering review of stable support is a highly critical part of foundation design. However, there are not many professionals who can conduct engineering review of tower crane foundation and, if any, they

have information only on a small number of cranes in which they have hands-on experience. To address such problems, this study proposes automatic design algorithm for fixed tower crane foundation with piles. Conclusions drawn herein are as follows.

Tower crane stability review items were analyzed to identify review items required for base plate design and pile design. As shown in Fig. 1, base plate design requires review of bearing force of soil, overturn and shear stability. Pile design needs review of bearing capacity and pile reaction and pile pull-out stability as well.

A step of determining pile addition at the time of foundations design was proposed. Such step proceeds in the order of reviewing bearing capacity, shear and overturn of base plate first and sizing up base plate or adding piles, subject to stability determination. If piles are to be added, piles are designed and bearing capacity, pile reaction and pile pull-out are reviewed to determine. If stability is not secured, pile design needs to be revisited.

Foundations design process was proposed to define the concept of stability review process. Tower crane information and site condition data are imported, which will be applied to subsequent studies and expected to increase the operational efficiency of site crews as well.

ACKNOWLEDGMENT

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