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VERTICAL DELIVERY CHALLENGES FOR HIGH-RISE BUILDING CONSTRUCTION

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Abstract: As buildings continue to be designed much taller than before, the increasing height of buildings produces problems of vertical delivery in efficiency, safety and cost. To address these challenges, researchers and engineers are applying new technologies and management strategies to improve vertical transportation of resources. This paper discusses state-of-the-art solutions to problems and successful examples of implementation in three selected areas: temporary hoists, concrete pumps, and tower cranes.

1 INTRODUCTION

The vertical delivery of materials and labour on construction sites is mainly achieved using temporary hoists, tower cranes and concrete pumping systems. However, the increasing number of high-rise building projects worldwide has introduced new challenges in vertical delivery (Chang et al. 2011). As the height of buildings grows, the efficiency of vertical transportation drops exponentially, thus affecting the safety, cost and overall schedule of projects. In particular, those sites in spatially-constrained urban areas are limited in the number of equipment that can be installed on site. This paper introduces the development of technology and management methods to enhance the safety and efficiency of on-site vertical delivery.

First, construction temporary hoists are the main method of transporting labour. Unlike materials that can be lifted during the night, workers only can be transported at the time of executing their assigned tasks (Moonseo 2013). Therefore, a significant amount of unproductive time is spent being transported to their designated floors, particularly in high-rise buildings. To counter this issue, current research introduces several methods to support decision making regarding hoist planning and operation. A case study and simulation experiments will show how operational strategies can improve the productivity of a construction hoist and reduce worker delays, which can significantly improve the productivity of labour.

Second, concrete is a common building material that is used throughout a project. Traditional methods of delivering concrete by crane and bucket are constrained by the limited number of cranes and weather conditions. The use of concrete pumps and an innovative method to reduce costs and guarantee constant flow will be highlighted.

Finally, tower cranes are used to lift and/or move heavy materials and large pieces of building components, and can be a big challenge in terms of safety. Special challenges for the use of tower cranes in tall buildings will be discussed.

2 CONSTRUCTION TEMPORARY HOIST

A construction temporary hoist, also known as a temporary elevator, construction elevator, or construction lift, is commonly used in building construction projects to lift materials and labour. For most building projects, hoists are leased or rented by the general contractor. Unlike a permanent elevator, temporary hoists are operated manually by an on-board operator, allowing direction changes or stops at any time according to the operator (Hwang 2009).

Hoists are commonly have single or double cages (1 or 2 cages per tower respectively) with a capacity varying from 25 to 35 people per cage (Chang-Yeon 2009). Capacity is reduced when materials and tools are carried with workers. The growing height of a building, limited number of hoists, and reduced capacity can make workers' movement between floors inefficient, resulting in a significant amount of time wasted waiting for hoists each day. For example, during the peak of construction at the Korea Convention and Exhibition Center in Seoul, South Korea, it took approximately 130 minutes to lift 1200 construction workers to their designated working floors (Moonseo 2013).

Hoist operations are also affected by weather and local regulations, which may restrict hours of operation. Therefore, optimized planning and operation of construction hoists is needed to reduce worker waiting time and improve overall schedule performance. Furthermore, since workers typically begin work simultaneously every morning, the biggest challenge of hoist operation optimization is to solve peak-hour congestion.

2.1 Construction Temporary Hoist Operation Optimization

Vertical transportation of construction workers and materials can be viewed as a cyclic operation, making it suitable for analysis and optimization using discrete event simulation (Ioannou and Martinez 1996; AbouRizk 2010). For the past decade, simulation techniques have proved effective in the development of improved lifting plans (Ahn 2004). The introduction of genetic algorithms to these models (Shin et al. 2010), lead to optimal lifting plans that minimized worker waiting times.

Strategies used in the elevator industry, such as zoning (Newell 1998), can be applied to minimize worker transit time in high-rise construction (Moonseo 2013). Zoning is used to divide buildings into groups of continuous vertical floors. These groups form zones that can be reached only by specifically assigned hoists. In this way, the number of stops each hoist has to make is reduced, and the total time to deliver a workforce is reduced. The challenge with this method is determining the optimal zoning configuration based on continuously changing conditions, including lift demand, floor demand, and number of floors. To solve these issues, a computer simulation incorporated with artificial intelligent and dynamic lifting demand was developed (Moonseo 2013). A case study in Korea shows that the application of zoning can significantly reduce the total lifting time by 40% (300 workers and the completed building height is 240 m).

Another, less restrictive way to reduce lifting times for sites with multiple hosts is to coordinate the hoists by optimizing the stops for each hoist when calls come for a pick up. The scenario of taking workers from the ground floor to their designated floors can be simplified to a travelling salesman problem (Cho 2013), which can be mathematically solved by a branch and bond algorithm. Combined with discrete event simulation, the hoist route becomes the objective of the optimization function. This method has been shown to improve the efficiency of hoist operations (Cho 2013).

Another alternative for dealing with peak hour congestion is to apply staggered arrivals to the workers' daily schedule. Staggered arrivals have been studied in transportation and elevator planning for office buildings (Kamleh 2014) to reduce the queue during morning peak hours. This concept achieves lower overall waiting times. While it is hard to manage arrival times of workers and visitors using elevators in operating office towers, construction sites may have more flexibility. Project managers can arrange staggered work hours to reduce the congestion at the start of the day.

2.2 Construction Temporary Hoist Alternatives

Because the elevator mechanical room is installed at the top of the building, the installation of the elevators happens after the building has been topped off and the roof has been completed and waterproofed. Due to recent developments in elevator technologies, elevators can be used at the early stages of construction by installing mechanical rooms that climb with the construction, eventually becoming the permanent elevator system. These jump lifts provide an alternative to exterior hoists for labour movement with several advantages: the elevators are up to 5 times faster than hoists and are unhindered during extreme weather. However, they are not typically designed to carry the weight of most construction materials, tools and equipment, and they are expensive. As far as the authors have been able to find, the first use of a jump lift in North America is currently underway at One Bloor in Toronto, Canada.

As hoists become the bottleneck of labour transportation during peak hours for high-rise building construction, a smarter and more efficient lifting plan is required to improve hoist productivity. Recent advances in elevator technologies are taking some of the pressure off hoists, allowing them to focus on material and heavier loads.

3 CONCRETE PUMPING SYSTEM

The majority of tall buildings under construction in Canada are concrete. The significant increase in the use of concrete in tall building construction is attributed to improvements in concrete technology including strength, admixtures, pumping, construction techniques and structural systems (Rizk 2010). To accommodate tight construction schedules, hydraulic concrete pumping has developed as a fast and economical method of transporting concrete due to its reduction in labour requirements and the ability to deliver continuous concrete pours (Mechtcherine et al. 2014). The traditional crane and bucket method of delivering concrete is limited by the availability of cranes, the effects of heavy winds, and its inability to deliver a continuous flow of concrete. Pumping methods aim to address these limitations.

3.1 Factors Affecting Concrete Pumping

Concrete pumping for construction purposes is directly related to two major factors, concrete composition and the mechanical characteristics of the pumping equipment. Concrete mix composition affects the properties of fresh concrete such as bleeding, segregation, viscosity, cohesion and compactness (Ngo et al. 2012). These properties have a significant impact on the pumpability of the concrete and the formation of a boundary layer (also referred to as lubrication layer), which forms at the interface between the concrete and the pipe (Choi et al. 2014). This lubrication layer is crucial to reducing the shear stress between the concrete flow and pipe wall to achieve the lower pressures necessary for pumping (Mechtcherine 2014).

Construction concrete is made of cement, water, aggregates, chemical additives and mineral admixtures. The concrete pump applies pressure through a pipe that is made from abrasion resistant material, and drives the concrete through the pipe. The cement paste deforms into the lubricating layer against the internal wall of the pipe. During pumping, this layer surrounds the “plug” along the center of the pipe that is made up of coarse aggregates and cement paste (Mechtcherine 2014). It is important for there to be enough mortar content in the fresh mix to form a lubrication layer throughout the length of the pipe, but that the mix composition remains homogeneous without segregation of the concrete constituents (see Figure 1).

The formation and effectiveness of the lubrication layer is highly dependent on the concrete mix. Another direct effect of the rheology of fresh concrete is the transmission of forces within the concrete plug. For the given equipment, adjusting the concrete mix can achieve lower necessary pumping pressures. Furthermore, using high pumping pressures can alter the properties of fresh concrete. For example, increased pumping pressures can lower air content, which increases the concrete’s plastic viscosity, leading to potential blockages. The challenge that engineers face is to find an optimal concrete mix to reduce pumping pressure without negatively impacting other functions. There are various ways of optimizing the mix to achieve this (Ngo et al. cited 2012).

- Increasing the water to cement ratio (w/c) of the concrete makes the concrete flow more easily.
- If maintaining the w/c is necessary, increasing the paste volume while maintaining the w/c can achieve similar but less effective results.
- Similarly, a fine sand (0.5 mm) content of up to 10% has a very small effect on the plastic viscosity of the concrete yet improves the concrete's slump. Beyond a 10% fine sand content however, the viscous constant begins increasing in a linear fashion.

A superplasticizer dosage of approximately 0.4%, which results in a slump of 21cm, produces a linear decrease in the viscous constant. Beyond this dosage, however, superplasticizers have no additional effect on the viscous constant.

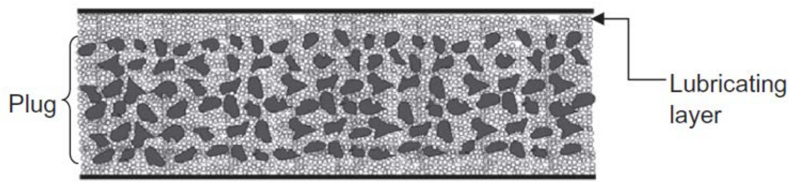

Figure 1 Schematic View of Plug Flow of Concrete during Pumping (Mechtcherine 2014)

3.2 Emerging Solutions

To determine the required pumping pressures of concrete, standard tests such as the slump test or flow table test are used. The results from these tests are used as important inputs for estimation. The issue with this conventional way of determining pumping pressures is that monographs are often unable to account for extreme values of specific parameters, such as long pipe lengths or large spreads (Mechtcherine et al. 2014). More importantly, the concrete mix ratio which has a great influence on concrete attributes is ignored. While the traditional test is a good indicator of the yield stress of the concrete, it is a very poor descriptor of the plastic viscosity, which plays a major role in determining the pumping pressure required. Although concrete testing devices such as rheometers and viscometers can better estimate the palpability of concrete, their complexity and lack of mobility make them unpopular for on-site testing of concrete (Mechtcherine et al. 2014). To better describe the pumpability of concrete with a device that can be implemented in the field, the Sliding Pipe Rheometer (Sliper) was developed ((Mechtcherine 2014). The crucial difference Sliper has compared to regular rheometers is its very close adaption to real pumping processes as well as its relatively simple and robust setup.

To further improve the pumping of concrete, testing in which electromagnetic currents are externally applied onto the pipe has been conducted (Choi 2014). This eases the formation of the lubrication layer, contributing to lower pumping pressures and increased flows. The electromagnetic field allows water to move more freely in the mix, and to form a thicker, more efficient lubricating layer. As a result of water's natural polarity, water molecules are typically attracted to each other and form clusters of approximately 100 water molecules at normal temperatures, reaching a thermodynamic equilibrium state between the association and dissociation of molecules in the cluster (Choi 2014). The application of the electromagnetic field allows the molecules to break off into single molecules or smaller clusters, which results in higher activity in the water and facilitates the formation of the lubricating layer. Using a special electronic called control device fluid liner, it was found that the optimal frequency range of the magnetic field was between 80 Hz and 1.1 kHz dependent on the composition of the mixture (Choi 2014). When these magnetic fields were applied, the pressure necessary to achieve pumping conditions was reduced by nearly 30% regardless of the concrete design mix. At equal pressures, pumping with an electromagnetic field resulted in a 15% increase in concrete flow through the pipe.

The reduction in pumping pressure makes it possible to use less powerful pumps, thereby reducing costs and improving the construction of tall buildings by facilitating concrete delivery. Although the magnetic field was only applied to a 20 m length of pipe, pressure measurements along 1000 m of pipe downstream showed an approximately linear relationship. This implies that the lubrication layer is preserved through the piping during the pumping process (Choi 2014). This can be a major benefit for the transport of concrete in tall building construction.

3.3 Summary

Concrete is a common building material in tall building construction. Advances in concrete mix design and the implementation of new technologies, such as the application of an electromagnetic field, can help reduce costs and improve overall process efficiency.

4 TOWER CRANES

Tower cranes are used on construction sites to lift materials or heavy building components. For those sites located in urban areas, crane activities are confined, and any accident can lead to serious consequence to workers and pedestrians. The use of tower cranes during tall building construction is even more challenging because the increasing height adds problems of visibility, wind load and safety issues for the operator.

4.1 Visibility Problems

Increased height often comes with visibility problems due to congested construction sites, the location of the crane cab, and intensified weather conditions. Limited visibility forces the operator to rely on radio communications when they are unable to see the load or the crew providing hand signals. In these cases, communication, responses, and productivity become slower. Typical visibility problems include blind lifts, sight distance, and poor weather.

- Blind lifts occur when crane operators experience partial obstruction of the loading or unloading working zone or the travel path (Shapira and Lyachin 2009). In these cases, the reliance on signals and radio communications to guide the lift becomes necessary, but it brings an increased risk of misunderstandings and accidents.
- Tower crane operators enjoy a bird's eye view of the construction site, which contributes to good sight coverage of the site. However, as the height of the tower crane increases with the building, the operator's perspective of the loading and working zone becomes nearly vertical, thereby losing some depth perception. Additionally, the operator's ability to distinguish details decreases with the distance to the target. Long sight distances and vertical sight angles lead to difficulty in precise lifts or placements, which forces operators to depend on signals and increases the risk of accidents (Shapira et al. 2008).
- Poor visibility due to lighting or weather is an important contributor to crane problems. Operators sometimes have to work during dawn, dusk, night, or in direct or reflected sun glare (Shapira et al. 2008). These circumstances reduce their ability to distinguish their target from the surrounding visual noise. This can cause eye fatigue and visual images to be blurred. Weather-related visibility problems may also result from heavily overcast skies, rain, snow, fog or dust. Visibility works both ways as operators may be challenged to see the loads that they are lifting, while others are challenged to see the tower crane. For example, in 2013, a helicopter hit a tower crane atop a 235m building that was under construction in central London, UK (**BBC 2013**).

Resent research has made progress in developing 3D and 4D simulation tools to optimize tower crane and other equipment layout to reduce obstacles for operators during construction (Al-Hussein et al. 2006). However, planning strategies have limitations in real-time management. New technologies have been deployed on cranes to monitor their operations using wireless sensors and GPS (Kim et al. 2003). Proper training of operators by increasing their situational awareness of construction site layouts has proven effective in reducing accidents (Cheng and Teizer 2014).

4.2 Wind Loading Effect

Working at heights is also associated with higher wind speeds. Wind speeds may be represented using the power law, shown in Equation 1 (Sen et al. 2012), where Z is the elevation, V is the wind velocity ($V_2 > V_1$), and n is the exponent that represents local climatology, topography, surface roughness, environmental conditions and weather stability.

$$[1]\ \left(\frac{Z_1}{Z_2}\right)^n = \left(\frac{V_1}{V_2}\right)$$

Using average winter wind speeds for downtown Toronto shown in Table 1 (Environment Canada 2003) as the reference speeds for Z_1=30m and Z_2=80m, an exponent of n=0.34 was calculated. This is a reasonably good fit with the general estimate of n=0.4 for a city area with tall buildings (Sen et al. 2012). With those two exponents, the average winter wind speed at 150m above ground level, or approximately 50 storeys, can be extrapolated using the power law as being between 8.0 and 8.8 m/s, almost double the speed at 30m. At wind speeds greater than average, there is a significant danger in underestimating the impact of doubling the apparent wind at ground level when lifting large loads up a tall building.

Table 1: Average Winter Wind Speed in Toronto (Environment Canada 2003)

Building height above ground level (m)	Average wind speed in winter (m/s)
30	4.6
50	5.4
80	6.4
150	8.0-8.8

Operation guidelines (not regulations) for tower cranes often cite 13m/s (30 miles per hour) as a maximum wind speed for crane operations, with warnings that operations may cease at 9m/s if conditions warrant (Worksafe BC 2015). This may be in consideration of the changes in wind speed with height that may not be obvious on the ground. Although the tower crane is designed to withstand much higher wind speeds while out-of-service, in-service wind speeds are lower because of the effect the wind has not only on the crane itself, but also on the load that it is lifting. Therefore, high wind speeds can increase the frequency in which cranes are out-of-service. Since heavy components such as glass curtain walls or concrete beams are primarily transported by tower cranes, their serviceability directly affects the overall schedule.

The wind can exert a significant load on the crane structure itself (Watson 2004) depending on the direction of the wind relative to the jib and on the size, weight, and proportions of the item being lifted. Formwork, for example, may impose forces well in excess of its weight if the load is moved by the wind from its expected position directly below the jib block. If the wind is from the side, then the displacement causes side loading of the jib, something for which it may not be designed to withstand. If the wind load is from behind, the movement can increase the load radius beyond the end of the jib and significantly reduce its capacity (Watson 2004). Additionally, high winds can cause movement of the load and directly strike workers or pedestrians. A moving load can also cause equipment or materials to fall when struck by the load and result in injuries. In 2008 in downtown Toronto, the cable from a derrick crane on the top of a topped out but not yet complete 51 storey building was caught in winds from a winter storm and broke windows between the 30th and 40th floors of the tower, showering glass at ground level (Reinhart 2008). The increased length of the crane's tower and jib highly increase the complexity of its structure, making structural analysis more difficult, and causing more problems while installing and dissembling. Any malfunction of an element could cause the failure of whole structure, leading to a catastrophe.

Another potential hazard is the behavior or wind load on a tower crane when erected alongside a building (Mara 2010). The presence of the tower crane alongside the building significantly changes the aerodynamics of the building because the tower crane alters the geometric cross section of the building.

Based on a wind tunnel study (Mara 2009; Mara 2010), two recommendations were made to minimize wind loading effects on tower cranes.

- First, the location of tower cranes shall be restricted to the middle portion of a building face to reduce torsion forces on the crane. When tower cranes are placed near the center of building face, the wind load on the crane will match that of the building. As the cranes approach the edge of the building, the mean and fluctuation values of torsion forces significantly increase.
- Second, the tower cranes should be located along the leeward face of the building to reduce the wind loading due to the shielding effect provided by the building.

4.3 Safety Management

The main causes of tower crane accidents are carelessness, negligence or misjudgment of participants, inadequate training, sub-contracting operators, and pressure from tight schedules (Tam et al. 2011). Carelessness is often cited in conjunction with other factors, such as working too close to a high-voltage line or being struck by a moving load (McCann 2009). Therefore, safety management and safety culture on site are crucial for the decrease of accident rates related to tower cranes. The following factors influence on-site safety performance.

- The length of work shift for tower crane operators usually extend beyond normal working hours because materials are often delivered before and after work hours. Hence, the crane operators are typically the first to arrive and the last to leave. Further, due to the time and effort required for operators to get into the crane cab, managers tend to minimize shift changes. The long, repetitive, and monotonous work may cause the crane operator to lose focus and alertness. With the increase of both physical and mental fatigue, the chances of accidents increase as well (Shapira and Lyachin 2009).
- Operator aids includes crane monitoring and the information received from signalers and crews. Communications between operators and signalers are usually achieved by radio or similar technologies, where the instructions from a signaler plays an important role. Hence, signaler shall be trained to properly instruct crane operations. Crane safety monitoring systems include digital-display load indictors, 2D/3D crane operation graphic displays, GPS based weather and wind warning systems, anti-collision and zoning systems for sites with overlapping cranes, and video cameras that enable the operator follow the review of loading (Peurifoy 2002; Shapira et al. 2008, 2009). These new technologies often compensate for human fallibility and prevents accidents (Neitzel et al. 2001).
- Human resource management helps to ensure that the operator has the characteristics required to ensure a safe working environment. Objective measures of operator skills include formal training and certifications, accumulated experiencem and safety record (Shapire 2008).

To sum up, the chances of tower crane-related accidents significantly increases when safety management is deficient. Tower crane safety can be achieved through site-level and company-level actions. Site-level actions include training, preventive actions, monitoring, on-going inspections and balanced rewards and punishments (Ng et al. 2005). Safety for company-level management are usually measured by the allocation of resources, planning and scheduling, and strictly enforced inspection policies and procedures. (Shapira 2008).

5 CONCLUSION

Vertical delivery has a significant effect on the overall performance of the schedule for tall building construction projects. To address this challenge, technologies and management strategies are being developed to improve the efficiency and safety performance, while at the same time reducing the cost of vertical transportation on construction sites.

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