Identification and Analysis of Factors Affecting Safety on Construction Sites with Tower Cranes

Aviad Shapira, F.ASCE[1]; and Beny Lyachin[2]

Abstract: Tower cranes are the centerpiece of production on today's typical building construction sites. Tower cranes hoist and transport a variety of loads near and above people, working under crowded conditions, occasionally with overlapping work zones, and often under time, budget, and labor constraints. This work regime further increases the safety risk on sites that are inherently hazardous workplaces. This paper presents the results of a study that identified the major factors affecting safety in tower-crane environments and evaluated the degree to which each factor influences ongoing safety on site. Use of statistical data on accidents was ruled out as a source of information due to the countless number of incidents that go unreported, the common inability of statistics to provide root causes, and the questionability of statistics as a predictor of accidents. The research methodology was therefore based on comprehensive questioning of an expert team that included the safety managers and equipment managers of leading construction companies. With the limited resources available for safety improvement and accident prevention, greater attention must be paid by all parties involved to those factors evaluated as highly affecting site safety due to tower-crane work.

DOI: 10.1061/(ASCE)0733-9364(2009)135:1(24)

CE Database subject headings: Accidents; Construction sites; Cranes; Hazards; Human factors; Safety.

Introduction

Mobile cranes—truck mounted and crawler—are the machines of choice in North America, indeed the backbone of the United States construction industry and perhaps the most visible representative of the American construction equipment culture (Shapira and Glascock 1996; Shapiro et al. 2000; Peurifoy et al. 2006). It is no wonder, then, that most of the literature published in the United States on construction equipment and site safety addresses primarily mobile cranes, and only very little of it, if at all, refers to tower cranes. However, the presence of tower cranes—the most conspicuous symbol of construction in Europe and the industrialized Far East—has gradually increased in North America in recent years (Shiffler 2006; Shapira et al. 2007). Whereas until recently they were seen almost only on sites on which no other lifting solution could be used (i.e., high-rise construction or tight sites), today they are increasingly also favored by American contractors for projects that traditionally would employ mobile cranes. Hence, the need arises to address safety issues concerning tower cranes and their operation in a culture that is slowly embracing these machines but has not yet been broadly exposed to such issues, nor has it yet developed methods and tools to deal with them.

[1]Associate Professor, Faculty of Civil and Environmental Engineering, Technion-Israel Institute of Technology, Haifa 32000, Israel (corresponding author). E-mail: avishap@technion.ac.il

[2]Requirements Manager, Siemens Transportation Turnkey Systems Ltd., 132 Menachem Begin Blvd., Tel Aviv 67021, Israel; formerly, Graduate Student, Faculty of Civil and Environmental Engineering, Technion-Israel Institute of Technology, Haifa 32000, Israel.

Note. Discussion open until June 1, 2009. Separate discussions must be submitted for individual papers. The manuscript for this paper was submitted for review and possible publication on April 2, 2007; approved on July 1, 2008. This paper is part of the ***Journal of Construction Engineering and Management***, Vol. 135, No. 1, January 1, 2009. ©ASCE, ISSN 0733-9364/2009/1-24–33/$25.00.

It is recognized that due to their configuration and operation concept, mobile cranes are potentially more "dangerous" than tower cranes (Shapiro et al. 2000; Yow et al. 2000; Peurifoy et al. 2006). The use of tower cranes, however, entails its own safety problems as well; with the large-area work envelopes of tower cranes that commonly cover the entire site and the crane that often oversails beyond site boundaries, these safety problems have a major bearing on the overall work safety on site.

This paper presents the results of a study that sought to identify the major factors affecting ongoing safety on construction sites with tower cranes. Furthermore, based on the collective knowledge of expert practitioners in equipment management and safety management, who were involved in the process of identifying these factors, the study also sought to evaluate the degree to which each factor influences on-site safety. Factors with higher degrees of influence should be given special attention; a larger share of the limited resources available for the improvement of construction site safety should be allocated to keep them in check.

With a view to quantification of safety hazards, the current study is the first phase of a research plan aimed at developing a method for the computation of safety indices that objectively and realistically reflect the state of ongoing site safety. Such quantitative indices would indicate the major hazards with a continuous presence on site and facilitate the comparison of safety levels on various sites operated by the construction company for better allocation and utilization of limited resources.

Background

Tower-crane work constitutes a critical component in the range of elements that make the work environment of construction sites essentially hazardous (Shepherd et al. 2000; Neitzel et al. 2001). Factors that affect construction site safety due to the work of tower cranes have attracted only moderate attention; they are

J. Constr. Eng. Manage., 2009, 135(1): 24-33

commonly addressed indirectly and partially within the broader treatment of site safety or of crane work in general (Dickie 1981; Nunnally 2000). Literature addressing crane safety that explicitly suggests tower crane related risk factors or safety hazards is limited, and therefore an initial list of such factors, which was compiled in the current study, was based on the small quantity of literature available (MacCollum 1993; Hinze 1997; Leung et al. 2000; Shapiro et al. (2000).

Common to all of these, with the partial exception of Shapiro et al. (2000), is the lack of *quantitative* treatment at the individual site level. Several studies suggest quantitative models for the assessment of safety management or other indicators on site, through which safety itself can be assessed (Fang et al. 2004; Ling et al. 2004; Ng et al. 2005). These models, however, are inferential by nature, and therefore do not necessarily reflect the actual risk that is present on site, nor do they provide an indication as to the cause of this risk. Hammer (1989) maintains that the core of the problem of implementing and managing safety is the inherent difficulty to *measure* safety. If both winds and inexperienced crane operator, for example, are among hazardous conditions on the site, which has a greater potential impact? How can we measure safety level on site if the situations and factors involved are innately unquantifiable in any *direct* way? These and similar questions are indeed hard to answer due, among other things, to the different contextual conditions that exist on any individual site.

Thus, the current study attempted not only to identify factors affecting safety but also to evaluate them, as a first step in developing a quantitative method for the direct assessment of safety hazards in a tower-crane operation environment.

Methodology

Following an initial list of factors compiled from the literature, numerous visits to construction sites and open discussions with site personnel, mainly crane operators and superintendents, were conducted. Tower-crane work was observed from both the ground and the operator cab. This pilot proved to be an important learning stage; it also helped expand the initial list.

During these visits, an inventory of incidents—major and minor accidents, as well as near misses—was compiled based on stories gathered from crane operators and other site and company functionaries. Likely root causes of these incidents were also solicited. Altogether, there were 61 such incidents, which were analyzed, classified, and tabulated by Shapira and Lyachin (2004). Thus, with the additional input from this inventory, the final list of factors that served as the departure point for the *structured* knowledge elicitation in the current study was formulated.

The main problem now lay in identifying an appropriate, structured method for obtaining information and recovering knowledge about these factors, their relevance to tower-crane work, and their degree of influence. The solution applied to this problem was deemed crucial for the success of the study. The rest of this chapter, therefore, elaborates on both the problem and its solution.

Statistics as Knowledge Source

Statistics on construction accidents involving tower cranes could have been a reliable source of information for this kind of study. In reality, however, statistics suitable to serve the purposes of the current study hardly exist—for tower *or* mobile cranes. First, crane accidents are commonly reported only in cases of fatalities or severe injuries (Fair 1998). Therefore, numerous cases simply do not make it into the statistics, even if they are reported within the construction company. These cases, which may involve injuries or "only" cost damages, constitute the majority of crane-related accidents. Furthermore, near-miss incidents, some of which have the potential of turning into bad accidents, are often not reported even within the company. All in all, accidents are subject to gross under-reporting (Butler 1978; McDonald and Hrymak 2002).

But even when statistics and accident records are at hand, they usually provide information on the circumstances, nature, outcomes, symptoms, and even proximal causes and contributing physical factors of accidents; only very rarely do they go all the way in providing the root causes of the accident investigated (Häkkinen 1993; Hinze et al. 1998; Abdelhamid and Everett 2000; Neitzel et al. 2001; Beavers et al. 2006). As such, statistics and investigation files are unlikely to be useful as a source on safety hazards and the prevailing on-site conditions that cause them. As Hammer (1989) stated: "Accident statistics . . . do not answer questions about what causes accidents . . . They do not indicate relationships between causes and effects." He adds that "even where accident and injury statistics can be useful, they are often incomplete, inaccurate, and therefore incorrect."

There is another fundamental debate on the usefulness of accident-related information in reflecting the safety reality on site. Is a site that has experienced an accident more "dangerous" than one that has not? Can we learn from one incident about the general level of safety on site? Many researchers have concluded that the answer to both questions is negative. Laitinen et al. (1999), for instance, maintain that "the use of accidents as a safety indicator of a single building construction site is in most cases impossible… many sites have no accidents and it is not possible to say whether they are safer than other sites with four or five accidents." McDonald and Hrymak (2002) conclude an extensive literature survey on this subject by stating: "It can be said that accident frequency cannot be considered to be a robust measure for research purposes."

Thus, after ruling out the use of statistical data on accidents, another source of knowledge was needed to identify the factors affecting ongoing construction site safety, which are related to tower cranes, and to assess the magnitude of such factors. Researchers who encountered similar problems in the past turned to experts (Cho et al. 2002; Lee and Halpin 2003). Harms-Ringdahl (2001) maintains that questioning of experts is a viable option under such circumstances, assuming that an expert has accumulated an abundance of knowledge based on extensive experience. Therefore, elicitation of knowledge from experts was decided upon as the method to be used in the current study.

Expert Panel

The panel that served as the knowledge source for this research comprised 19 experts who were either the safety or equipment managers of the top ten construction companies in Israel (D&B Ranking 2003). These leading companies are recognized for their well-developed planning and management culture. Over the years, they have built the most ambitious building and engineering projects in the country and their sites excel in the application of advanced construction technologies and high utilization of mechanization. Most of the companies were also involved in similar construction projects overseas.

With a steady number of over 1,000 tower cranes operating in

J. Constr. Eng. Manage., 2009, 135(1): 24-33

Israel during the past 2 decades (CIS 2005), this small country (population 7 million) exhibits a typical tower-crane culture, and therefore constitutes an appropriate setting for any research relating to tower cranes. [For comparison, the number of tower cranes in the United States, with its population of 300 million, was also estimated for years at 1,000 (Bishop 2001; Hampton 2004), until it has recently started growing and is now estimated at 1,500 (Shapira et al. 2007).]

All of the experts—nine equipment managers, nine safety managers, and one who held both positions—were experienced professionals. Their cumulative tenure in their current positions was 310 years (mean of 16.3 years), and six of them had served in their current positions for more than 20 years. All were exposed to extensive work with tower cranes throughout their career, both in Israel and abroad. The companies they worked for owned and operated large fleets of 10–61 tower cranes each, totaling 279 cranes—nearly 30% of the entire tower-crane population in the country.

As a result of all the above, these practitioners were not only the country's top professionals in their fields but were, in fact, top-notch experts by any objective measure.

Knowledge Elicitation from Experts

Two rounds of face-to-face interviews were conducted by both writers with the expert safety and equipment managers. The first round included in-depth, 2–3 h long interviews with all 19 experts. These interviews were preceded by letters mailed to the experts that provided the background, objectives, and methodology of the study. Each interview opened with several open-handed questions in which the interviewees were requested to offer their assessment as to the factors affecting safety in working with tower cranes. It was important to give the experts an opportunity to express their personal opinion and ideas before introducing them to the list of factors prepared and presented by the writers. In the second part of the interview, the experts were requested to address each of the factors on the list, provide their judgment and reasoning, and offer examples. These examples not only enriched the discussion and facilitated understanding; they were also vital in ensuring that the wording on the list of factors was not ambiguous. The final part of the interview focused on the relative-quantitative evaluation of each factor's impact, as described later on (see "Degree of Influence").

As anticipated, the list of factors evolved from one interview to the next, with the addition of more factors, until it was finalized about half way through the first round of interviews. At this point, the initial list had almost doubled, which prompted the need for a second interview with nearly half of the experts.

The third and final phase of knowledge elicitation was conducted using basic elements of the Delphi technique for establishing consensus among remotely located individuals (Linstone and Turoff 1975). Following the two face-to-face interview rounds, the quantitative evaluations were analyzed. Mean degrees of influence were computed and deviations detected. All processed results were then distributed by writing to all experts, alongside their own evaluations. They were asked to review the material and consider amendments to their evaluations, particularly in case these significantly deviated from the mean evaluations of their colleagues. Interviews by phone then followed, during which various arguments provided by other experts on their evaluations were discussed. A few more changes resulted, and the list of quantitatively evaluated factors was made final. This concluded the knowledge elicitation phase of the study.

Finalization of Results

With a view to focusing the attention on major factors only, the list of factors resulting from the deliberations with the experts was narrowed down to include only factors that according to the experts exert a "moderate" to "very strong" influence [mean degree of influence (DOI) $\geqslant 2.5$; see "Degree of Influence"]. To further cement this process and its results, mainly to ensure that no important factor is left out, an additional group of eight senior project managers with tower-crane work experience was established. Similar to the participating equipment and safety managers, these project managers, each from a different company, were employed by eight of the same top ten construction companies in the country. Each had 11–24 years of experience as project manager, of which 6–18 years were managing large and complex projects involving tower cranes. It was deemed important to receive feedback from these qualified professionals, but due to the limited nature of their exposure to crane work, they did not appear suitable to actually serve on the study's core expert panel, and thus their involvement was limited to serve as a control group.

Each of the eight project managers was interviewed in the very same manner described above for the first round of face-to-face interviews with the expert panelists. The mean quantitative evaluations resulting from these interviews were then compared with those computed for the 19 experts. No meaningful differences were found, and thus the results supported and cemented the earlier findings.

The two subgroups comprising the expert panel, safety managers and equipment managers, were also compared, and here too, no meaningful differences were found.

Factors Affecting Safety

Table 1 presents the 21 factors identified in the current study that affect safety on construction sites due to the operation of tower cranes. The factors are grouped into four categories: project conditions, the environment, the human factor, and safety management. The complete description and analysis of these factors constitute the main body of the full report on the current study (Shapira and Lyachin 2004).

These 21 factors make up the final list out of an initial list of nearly 40 factors that were identified and discussed in the course of this study. Some of the factors removed in the narrowing down process are worth mentioning. Factors such as "crane setup and dismantling" were removed a priori since these are one-time operations or peak events; such factors are not present throughout construction on site, neither can they characterize ongoing crane work safety. [The removal of such factors, however, definitely does not diminish their potential hazardous nature or the need to address them properly; crane setup and dismantling, for one, is associated with a high rate of crane accidents (Häkkinen 1978; Suruda et al. 1999; Shapiro et al. 2000; Skinner et al. 2006).] Another example of a factor removed at this phase due to the same reason is crane operator turnover. If the resident operator is absent from work (e.g., due to illness) and a temporary replacement is brought in, risks due to crane operation may be increased—though only for a relatively short time, up to a few days at the most (until the replacement operator has become familiar with the site and work conditions or the site's operator has returned to work). There were other reasons for removing factors even prior to deliberations with the experts. Earthquakes, for ex-

J. Constr. Eng. Manage., 2009, 135(1): 24-33

Table 1. Factors Affecting Safety on Construction Sites with Tower Cranes

Factor	Definition	Description	Safety risk
Project conditions			
Obstacles and congested site	Obstacles (excluding power lines and shared-zone cranes) within the crane's work envelope; crowded site	With the aspiration of builders in urban areas to use the maximum land available for construction, sites in urban areas can become extremely crowded. Under such conditions, staging areas, various temporary facilities, equipment moving and operating on site, and adjacent buildings in close proximity, all constitute obstacles for crane work.	The more congested the site and the greater the presence of obstacles of various kinds, the harder and more accident prone the crane work.
Power lines	Overhead power lines located within the crane's work envelope	Overhead power lines often cross the site's air space, in which case crane work may be required to be carried out near them. Because of its configuration and height, it is quite possible that the tower crane's jib and hook block will overfly power lines.	The outcome of contact of the load or any part of the crane with energized power lines is usually fatal electrocution (Hinze and Bren 1996). Strict regulations set the minimum clearance between the lines and any part of the crane or load, but in extreme cases (e.g., strong winds), loss of control of the jib, trolley, or hook block motion may occur.
Blind lifts	Obstruction of work (loading, unloading, travel) zone from operator view	Crane operators experience partial obstruction of the work zone (loading/unloading or hook travel path) to various extents on almost all projects. This is due to the location of the cab relative to the erected building and staging areas. This is common particularly in high-rise construction.	When the operator has no line of sight with the load and receiving crew, complete and exclusive reliance on a signalperson becomes necessary. Problems in remote signaling or radio communication greatly increase the chances of accidents or "close calls."
Overlapping cranes	Overlapping work envelopes of two or more cranes	Construction projects often employ two or more tower cranes. Shared work zones of these cranes may result from: (1) geometric constraints (jib length and lifting capacity); (2) time constraints (one crane cannot satisfy all lifting needs); and (3) crane location constraints on site.	Commonly: the jib of the lower crane hits the cables of the higher crane. Also possible: loads hit each other, or load of one crane hits cables of other crane.
Sight distance and angle	Sight distance and angle from loading/unloading zones, as determined mainly by height of cab	A fundamental difference between tower cranes and mobile cranes is the location of the cab atop the tower crane, giving the operator good sight coverage of the site and work zones (Shapiro et al. 2000). However, the higher the crane, the greater the distance to the ground and the nearly vertical view of the load and work zone on the ground. Additionally, a nearly horizontal view occurs when the cab and work zone or travel path are almost at the same level.	The operator's ability to distinguish small details decreases with the distance to the target (e.g., for precise lifts or placement, to monitor the rigging of the load); likewise, the ability to discern a 3D image of the target (load, obstacle, work zone) declines sharply at vertical and horizontal view angles (Shapira et al. 2008). Consequently, all operator skills that depend on sight are impaired.
Cab ergonomics	Ergonomic level of operator cab for work convenience	Cab ergonomics include protection from rain and wind, climate control, cab size, view window size, convenience of seat and access to controls. This factor also pertains to access to the cab itself (by various types of ladders or by hoist).	Improper work conditions affect the operator, who must allocate physical and mental resources to cope with the inconvenience at the expense of focusing all energies on the work. Improved ergonomics reduce stress and chances for mistakes (Häkkinen 1993).
Length of work shift	Overtime (commonly into the night) as an indication of operator's and ground crew's fatigue	Workdays on construction sites typically extend beyond nominal duration and are therefore very long and often stretch into darkness. Hence, the tower crane operator, who commonly is first to arrive and last to leave, experiences exceptionally long days atop the crane.	The long, often monotonous work causes the crane operator, who sits all alone in the remote cab, to lose focus and alertness. With the increase of physical and mental fatigue, the chances of accidents increase as well. To a lesser degree, this is true with respect to the ground crew as well.

J. Constr. Eng. Manage., 2009, 135(1): 24-33

Table 1. (*Continued.*)

Factor	Definition	Description	Safety risk
Multiple languages	Different languages used on site by operator and by ground crew	With the increasing practice of employing foreign workers on construction sites, many sites are multilingual. Tower crane operator-signaler/rigger communication is commonly done by radio or similar technology, whereby the individuals involved may not have a command of the same language.	It is given that for routine crane work, even low level command of a shared language between the operator and ground crew may be satisfactory. However, in irregular lifts and in cases that necessitate quick decision, a less-then-perfect command of a common language may be hazardous (Batey 2006).
Operator aids	Optional operation aids, in excess of standard aids required by safety regulations, for increased safety	Optional operator aids include digital-display safe load indicators (SLIs), 2D/3D crane operation graphical displays, remote monitoring systems for various load parameters, sensor-based antisway systems, GPS-based weather and wind warning systems, anticollision and zoning systems for computerized control of sites with overlapping cranes, and crane-mounted video cameras enabling the operator to follow the load and view obstructed work zones (Peurifoy et al. 2006; Shapira et al. 2007, 2008).	This factor acts favorably, i.e., it helps reduce safety risk. Technological measures often compensate for human errors and prevent accidents (Häkkinen 1978; Neitzel et al. 2001). Note that an operator aid is not necessarily an advanced hi-tech product of the kind detailed to the left; as noted by Shapiro et al. (2000), "In many situations, the most effective safety enhancements are small and subtle measures…"
Type of load	Type of load, including rigging method	Certain loads may be more hazardous than others due to their features: (1) dimensions and weight; (2) configuration and packaging; (3) rigging method; (4) repetitive/regular versus random/irregular load.	When properly rigged and handled, loads per se do not pose different safety risks. It is the combination with other factors (e.g., obstacles and tight site, winds) that render some types of loads more hazardous than others.
Environment			
Winds	The effect of winds mainly on the lifted load but also on the crane itself	Wind intensity varies according to the site's geographic and topographic location, its proximity to the sea, the presence of adjacent buildings, season, and the height of the crane and lifted loads.	Tower cranes are built to operate in winds and to sustain winds up to intensities specified by manufacturers and regulations. However, operating in winds is still dangerous, particularly when combined with other factors such as sail-like load size, nearby obstacles, and inexperienced operator. Sudden wind gusts are especially dangerous. Additionally, extremely strong winds may topple over the tower crane itself ("Tower" 2000).
Weather	Extreme temperatures and other weather phenomena (excluding winds)	This factor deals with weather phenomena that affect crane work safety, excluding winds and poor visibility, which are addressed by other factors. Such phenomena include extreme temperatures and extreme humidity or dryness. The factor also includes rapid temperature changes and other weather conditions that affect the human body (Hammer 1989).	The risk stems mainly from the workers' need to allocate part of their physical and mental energies to coping with the weather, at the expense of full attention to the work. This refers mainly to the crane operator, but also to ground crew workers who are less protected. In bad weather, the environment can be hazardous as well (e.g., slippery surfaces in case of rain).
Visibility	Poor visibility (mainly of operator but also of others on site)	Poor visibility is caused by effects pertaining to lighting or to weather. Cases related to lighting are: (1) dark hours (dawn/dusk) or night work; (2) working in shaded areas (e.g., dark shafts) and passing between bright and dark work areas; (3) shade produced by the load itself; and (4) direct or reflected sun glare. Weather-related poor visibility may be the result of heavily overcast sky, rain, snow, fog, or dust.	In poor visibility conditions, the eyes are stressed and fatigue comes faster, images may be blurred, 3D vision is impaired, and details are indiscernible. Quick passages between bright and shaded areas weaken the operator's ability to accurately estimate height and distance (St John Holt 2001). All these increase chances for errors and accidents.

J. Constr. Eng. Manage., 2009, 135(1): 24-33

Table 1. (*Continued.*)

Factor	Definition	Description	Safety risk
Human factor			
Operator proficiency	Experience and proficiency of crane operator	Operator proficiency is the foremost ingredient in determining safety level of crane work and surroundings (Neitzel et al. 2001). Objective measures of operator skills are: (1) formal training and certification; (2) accumulated experience; and (3) safety record. Experience is measured first and foremost by the number of crane-operating years but also by the variety (e.g., crane types and models, project types and dimensions) to which the operator has been exposed over the years.	Operator proficiency plays a decisive role in: (1) making errors; (2) preventing dangerous situations before they develop; and (3) responding to others' errors once a dangerous situation has developed and preventing an accident (or lessening its damages). The shorter and less variegated the operators' experience and the lower their proficiency, the higher the safety risk. Operator experience is also critical for "feeling" the crane instinctively ("by the seat of his pants").
Operator character	Behavioral patterns and mental capacity of the crane operator	Measures of operator character that may affect the operator's conduct are: (1) levelheaded/impulsive; (2) disciplined/defiant; (3) tenacious/submissive; (4) vigilant/sluggish; and (5) focused easily distracted.	As in any man-machine system, in the operator-crane system the character of the operator and its bearing on the operator's conduct have a great effect on the chances of accidents.
Employment source	Crane operator is on the construction company's staff or is outsourced	Depending on local cultures, on the construction company policy, and on supply and demand, crane operators can either be on the permanent staff of the company, moving from one company's project to the next, or outsourced from a manpower company, usually for the duration of one project only (and often for a shorter-term service).	Outsourced operators, who have no direct employment contracts with the construction company, are often exploited and discriminated compared with permanent company employees, which may hamper their work and have negative implications on safety (Hinze 1997). On their part, outsourced operators tend to work overtime (particularly if paid by the hour) and "cut corners" so as to please their temporary employers.
Superintendent character	Behavioral patterns and mental capacity of the superintendent	In addition to generally being in charge of safety on site, the superintendent often has direct contact with crane work, the latter being a critical element of the production chain on site. Superintendent characteristics that may affect their contact with crane work and crane operators are, for example, authoritativeness, accountability, sensibility, and alertness.	In the likely possibility of conflict between speed and productivity on the one hand, and safety on the other hand, the superintendent's character may play an important role in maintaining or neglecting safety as far as crane work is concerned. [We do not, however, claim that safety and productivity are essentially in conflict with each other; as argued by Shapiro et al. (2000), "Measures taken to ameliorate risks…will also promote maximum equipment utilization and productivity."]
Signalperson experience	Experience of workers employed for signaling and rigging	Signalpersons, commonly also in charge of slinging, are referred to by many as "the operator's eyes and ears." But although they fulfill a critical function, they are usually undertrained and their service is often too short to gain adequate experience. Additionally, due to the good site coverage provided by the tower crane and its ability to almost concurrently extend service in different areas on site, there is not always a trained signalperson at hand where needed.	The situation that prevails in many cases, of undertrained and inexperienced signalpersons, increases chances of accidents in general. The situation is particularly riskier in cases of poor visibility and a great extent of blind lifts.
Safety management			
Site-level management	Safety management at the site level	Site-level safety management includes actions to increase awareness, training, preventive actions, monitoring, ongoing inspections, and rewards and punishment. Specifically pertaining to the crane are also daily morning inspections and maintaining a logbook and other record-keeping documents as required. Measures to assess site-level safety management are provided by Ng et al. (2005).	The safety climate on site, commonly dictated and dominated by the general superintendent, reflects on crane work as well. Chances of crane-related accidents greatly increase if site safety management is deficient. Superintendents are perceived as being a vital link between senior management and workers in promoting a positive safety climate (Lingard et al. 2005).

J. Constr. Eng. Manage., 2009, 135(1): 24-33

Table 1. (*Continued.*)

Factor	Definition	Description	Safety risk
Company-level management	Safety policy and management at the company level	Safety management at the company level is measured by the allocation of adequate resources for the following purposes (Firenze 1978): (1) company-wide safety array; (2) worker participation; (3) structured accident investigation process; (4) instruction and training; and (5) preparation, implementation, and monitoring of safety improvement plan. Other measures to assess company-level safety management are presented by Ng et al. (2005).	While this is not a direct factor, i.e., unsound company level safety management cannot directly cause an accident or have an impact on the outcome of an accident, this is certainly a potential risk factor. Not only do company safety guidelines affect practice on site, but also the manner in which company attitude toward safety is perceived by site personnel and workers has a bearing on their conduct (Jaselskis et al. 1996; Molenaar et al. 2002).
Maintenance management	Maintenance level of the crane and lifting accessories	This factor does not deal with the mechanical and other professional aspects of maintenance (which are assumed to be in accordance with manufacturer instructions), but with the management of maintenance: company policy, resource allocation, planning and scheduling, inspection and service procedures, monitoring, etc. Regulations commonly dictate and schedule inspections and testing, but usually these are only the minimum required for certification. The company's perception of safety is challenged particularly in cases in which high demand for lift power clashes with the need to service the crane.	Like any other machine, cranes must be properly maintained to extend their service life, to secure high productivity, and to ensure adequate safety levels (MacCollum 1993). Underserviced cranes and lifting accessories impede crane work safety and increase the chances of accidents; eventually they will also incur expenses higher than the costs initially saved, like with any savings on safety costs (Hinze et al. 1998).

ample, were deemed too exclusive (though they would most likely be treated differently in places such as Japan and Taiwan), and so was noise at levels that significantly exceed those common on construction sites. All eliminations conducted prior to the interviews later met the experts' approval.

Examples of factors that were presented to the experts, but which they disqualified almost unanimously *after deliberations* as to the extent of their influence (i.e., DOI$<$2.5), are "crane configuration" (i.e., free standing, externally braced to the building, internally climbing, rail-mounted traveling), "crane procurement method" (i.e., owned by the construction company or rented), "crane age," and "number of setup-dismantling cycles."

Degree of Influence

As mentioned, the collective wisdom of the 19-expert panel of equipment managers and safety managers yielded a list of risk factors and insight into their impact mechanisms (Table 1). It also produced an assessment of each factor's impact, namely, its DOI on the probability that an accident will occur, and on the consequences of such an accident. Eliciting knowledge from experts in lieu of extracting information from statistical records called for the experts to make their judgment and assess the impact of each factor based on experience with ample cases of accidents, both major and minor, as well as with near misses, all of which have been etched in their memory. This judgment quite naturally combines the experts' inseparable impressions from both incident rates *and* the severity of actual incidents.

The bars in Fig. 1 present the results in a descending order of the *mean DOI*, on a 0–5 scale ("no influence" to "very strong influence"). Each of the factors is represented by a bar composed of 19 squares, corresponding to the number of panel experts. Two of the factor bars ("superintendent character" and "obstacles and congested site") were, however, each given one "no influence" score, and are therefore composed of 18 squares only. The height of each of the squares making up the bars is proportionate to the DOI it denotes, and thus each bar height corresponds to the cumulative DOI accorded by the experts. The internal composition of the bars is by itself an interesting finding, as it provides an indication of the level of consensus among the experts as reflected by the distribution of each factor's assessments. For example, "maintenance management" and "operator character" exhibit an identical mean DOI. It is evident from Fig. 1, however, that there was much greater consensus with regard to "operator character" than with regard to "maintenance management:" the cumulative DOI of the former is composed of the degrees 3, 4, and 5 (i.e., "moderate" to "very strong"), while the experts accorded five DOIs to the latter (i.e., the entire spectrum between "very weak" to "very strong").

It should be stressed that the main purpose in questioning the experts regarding the DOIs was to gain an indication as to which are the strong versus weak factors, which are the consensual versus controversial factors, and what are the various arguments that justify the DOI accorded. By no means was the purpose to *rank* the factors, even if the presentation of the bars in Fig. 1 has the appearance of ranking. Likewise, there was no purpose whatsoever to determine the relative importance of each factor. For example, if "winds" scored a mean DOI of 4.0 and "cab ergonomics" scored 3.2, this by no means indicates that the impact of the former is 125% (4.0/3.2) that of the latter. Ranking a large number of factors and determining their relative weights cannot be done straightforwardly; it commonly requires the use of a multiattribute decision-making tool (Saaty 1980; Yoon and Hwang 1995). This phase of the study, not within the scope of the present paper, is treated elsewhere (Shapira and Simcha 2005).

Findings

Because factors that were assessed as having "weak" and "very weak" influence were dropped off the final list, there appears to be only a slight difference in bar heights in Fig. 1. However,

J. Constr. Eng. Manage., 2009, 135(1): 24-33

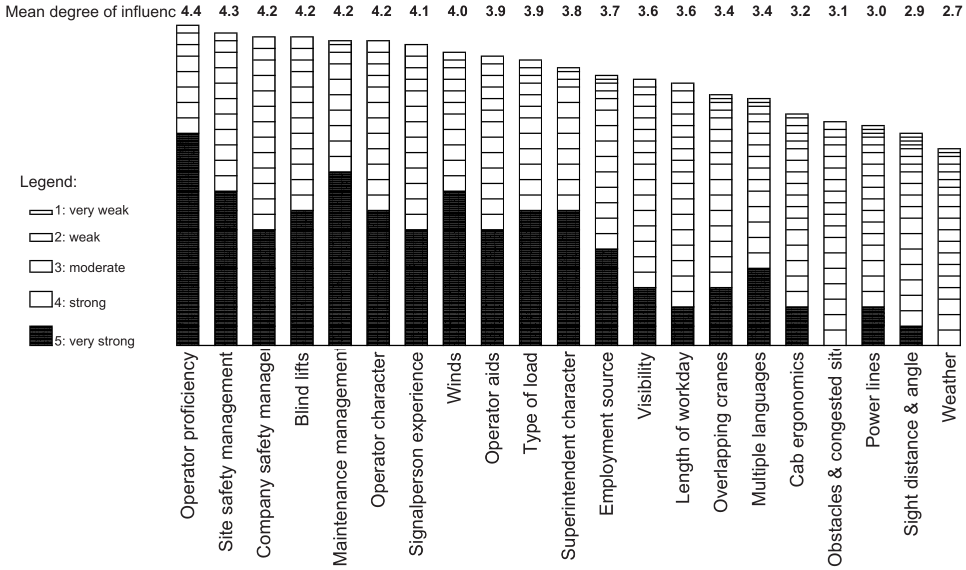

Fig. 1. Degree of influence of factors affecting safety on construction sites with tower cranes

differences between major and moderate factors are distinct, as are differences in the internal composition of the assessed influence. Hence, the following major findings are concluded:

1. "Operator proficiency" is the factor that scored the highest DOI. This assessment of the 19-member expert panel further cements the supreme significance attributed in the professional literature to the operator's role in maintaining safe operation of the crane (MacCollum 1993; Shapiro et al. 2000; Neitzel et al. 2001). It is interesting to note, however, that although 11 experts accorded this factor the highest DOI (5), higher than any other factor, two experts assessed its influence as "moderate" only, and one even assessed it as "weak." This finding echoes the aforementioned perception of the mobile crane operator as having a greater responsibility vis-à-vis safe operation of the crane than has the tower-crane operator;
2. Seven factors were assessed by the experts as "highly affecting" tower-crane related safety on site (i.e., mean DOI >4). These factors are predominantly those in the human factor and safety management categories. In fact, the entire category of safety management factors was determined to be "highly affecting." This is in line with current notions on the crucial role of safety management in improving and securing safety on site. Note that the high DOI attributed to safety management is the collective wisdom of a panel, only half of which was composed of safety managers, the other half being equipment managers with strong technical/engineering backgrounds;
3. Of the project conditions, only "blind lifts" was accorded a "high" DOI. This can be explained by the fact that in "regular" tower-crane work there are relatively few blind lifts, given the position of the operator atop the crane and the ensuing bird's eye view. Thus, blind lifts, more of a routine in mobile crane work, are perceived as exceptional, and therefore problematic, with respect to tower cranes;
4. Among the seven "highly affecting" factors, four yielded a higher consensus level than the others ("very strong" to "moderate" DOI). These are "company safety management," "blind lifts," "operator character," and "signalperson experience." Such a high consensus lends these factors a degree of robustness that may compensate for whatever little advantage other factors in this group of "highly affecting" factors have in terms of the overall DOI; and
5. Of the factors that scored lower (the right-hand bars in Fig. 1), most interesting perhaps is "power lines." The presence of overhead power lines within the crane's work arena is commonly accepted as a major hazard (Dickie 1981; Nunnally 2000). Yet, this factor was overall assessed as having only a moderate impact on safety in the vicinity of the crane (DOI$=3$). The rationale provided by almost all experts interviewed was that due to the enhanced awareness of the prospective danger of working near power lines, appropriate preventive measures are taken on site to minimize the risk. Some experts added that this was a *static* obstacle: it is always there, in the same place, inflicting unchanging concerns. Thus, it is a major hazard turned in practice into a minor one. While this rationale makes sense in a tower-crane environment, the picture is completely different when mobile cranes are involved. Electrocution due to contact (or near contact) with energized power lines accounts for more mobile crane accidents than almost any other cause (Suruda et al. 1999; Shepherd et al. 2000; Beavers et al. 2006). Note that the experts were in disagreement about this factor, as it scored the full spectrum of possible DOIs, from "very strong" to "very weak" (although with a clear majority ascribing it "moderate" influence). The higher DOIs were explained by the interviewees as reflecting the grave outcome should an accident indeed occur.

Conclusion and Future Research

This paper presented a list of 21 factors with an ongoing presence that affect safety in tower-crane environments. The list was generated and consolidated based on the experience and expertise of 19 senior safety managers and equipment managers from the top ten construction companies in Israel, which among them own and employ some 300 tower cranes. With a view to quantifying risk factors, the experts also assessed the influence of each of the

J. Constr. Eng. Manage., 2009, 135(1): 24-33

factors, thus making it possible to distinguish between factors that exert a strong influence and those that exert a moderate influence on site safety. With the limited resources available for safety improvement and accident prevention, greater attention must be paid by all parties involved (e.g., construction firms, regulatory and enforcement authorities) to those factors evaluated as highly affecting site safety due to tower-crane work.

The study reported in this paper constitutes the first phase of a broader research plan that aims to develop quantitative indices that objectively and realistically reflect safety levels on construction sites due to the operation of tower cranes. The development of such indices is envisaged to consist of the following stages: (1) identification of risk factors; (2) analysis and consolidation of factors; (3) determination of relative weights of factors; (4) development of risk scales for each factor; (5) development of methods to measure factors; and (6) integration of measured risks for the computation of an overall risk assessment index for any individual site. Of these six stages, the first two were presented in the current paper. Further research according to this plan will have to address issues such as the dynamic nature of most factors, desirable update frequencies, multiple-crane sites, and increased risk due to oversailing of cranes beyond the boundaries of the site. Due attention will also have to be given, in the final overall risk assessment, to the contribution of two other factors: the number of people exposed to the hazardous conditions on site, and the intensity of crane work. These two factors have a bearing on all other factors and therefore must be investigated with respect to them.

As we have learned in the course of conducting this research, accident investigation files commonly do not disclose root causes, due partly to the lack of knowledge on what factors to look for. It is hoped that the safety factors identified and assessed in this study can be helpful in modifying the way in which tower-crane accidents are investigated to the effect that root causes are more effectively exposed.

This study grew out of a typical tower-crane culture on the grounds of a chronic shortage of resources allocated for safety improvement. Its findings, however, may be equally useful for a developing tower-crane culture, and its methodology may also apply to other equipment cultures.

Acknowledgments

The writers gratefully acknowledge the cooperation of the equipment managers, safety managers, and project managers, whose experience and expertise played an indispensable role in the success of this study. This research was supported by the *Manof* Fund for Safety and Hygiene at the Workplace, National Insurance Institute of Israel.

References

Abdelhamid, T. S., and Everett, J. G. (2000). "Identifying root causes of construction accidents." *J. Constr. Eng. Manage.*, 126(1), 52–60.

Batey, J. (2006). "Can migrant crane ops speak our language?" *Cranes Today*, 383, 70.

Beavers, J. E., Moore, J. R., Rinehart, R., and Schriver, W. R. (2006). "Crane-related fatalities in the construction industry." *J. Constr. Eng. Manage.*, 132(9), 901–910.

Bishop, P. (2001). "Union city." *Cranes Today*, 318, 20–23.

Butler, A. J. (1978). "An investigation into crane accidents, their causes and repair costs." *Building research establishment*, Building Research Station, Garston, Watford, U.K.

Center for Information Services. (2005). "Construction equipment statistical report." *Report*, Ministry of Transportation, Holon, Israel.

Cho, H.-N., Choi, H.-H., and Kim, Y.-B. (2002). "A risk assessment methodology for incorporating uncertainties using fuzzy concepts." *Reliab. Eng. Syst. Saf.*, 78(2), 173–183.

Dickie, D. E. (1981). *Crane handbook*, Construction Safety Association of Ontario, Rev. Ed., D. Short, ed., Butterworths, London.

Dun & Bradstreet (D&B). (2003). "Dun's 100. Construction, development, and infrastructure companies." Israel, ⟨http://duns100.dundb.co.il/⟩.

Fair, H. W. (1998). "Crane safety on construction sites: an introduction." *Crane safety on construction sites*, Task Committee on Crane Safety on Construction Sites, ASCE Manuals and Reports on Engineering Practice No. 93, ASCE, Reston Va., 1–18.

Fang, D. P., Huang, X. Y., and Hinze, J. (2004). "Benchmarking studies on construction safety management in China." *J. Constr. Eng. Manage.*, 130(3), 424–432.

Firenze, R. J. (1978). *The process of hazard control*, Kendall/Hunt, Dubuque, Iowa.

Häkkinen, K. (1978). "Crane accidents and their prevention." *J. Occup. Accid.*, 1, 353–361.

Häkkinen, K. (1993). "Crane accidents and their prevention revisited." *Safety Sci.*, 16(2), 267–277.

Hammer, W. (1989). *Occupational safety management and engineering*, 4th Ed., Prentice-Hall, Englewood Cliffs, N.J.

Hampton, T. (2004). "New tower crane assessment exams raise operator certification debate." ENR, Safety & Health, October, 4, McGraw-Hill Construction, ⟨enr.construction.com/news/safety/archives/041004a.asp⟩.

Harms-Ringdahl, L. (2001). *Safety analysis: principles and practice in occupational safety*, Taylor & Francis, New York.

Hinze, J. W. (1997). *Construction safety*, Prentice-Hall, Upper Saddle River, N.J.

Hinze, W. J., and Bren, K. (1996). "Analysis of fatalities and injuries due to powerline contacts." *J. Constr. Eng. Manage.*, 122(2), 177–182.

Hinze, W. J., Pedersen, C., and Fredley, J. (1998). "Identifying root causes of construction injuries." *J. Constr. Eng. Manage.*, 124(1), 67–71.

Jaselskis, E. J., Anderson, S. D., and Russell, J. S. (1996). "Strategies for achieving excellence in construction safety performance." *J. Constr. Eng. Manage.*, 122(1), 61–70.

Laitinen, H., Marjamäki, M., and Päivärinta, K. (1999). "The validity of the TR safety observation method on building construction." *Accid. Anal. Prev.*, 31(5), 463–472.

Lee, S., and Halpin, D. W. (2003). "Predictive tool for estimating accident risks." *J. Constr. Eng. Manage.*, 129(4), 431–436.

Leung, A. W. T., Tam, C. M., and Liu, D. K. (2000). "Comparative study of artificial neural networks and multiple regression analysis for predicting hoisting times of tower cranes." *Build. Environ.*, 36(4), 457–467.

Ling, F. Y. Y., Ofori, G., and Teo, E. A. L. (2004). "Predicting safety levels of construction project sites." *Proc., CIB World Build. Congress*, Toronto.

Lingard, H., Blismas, N., and Wakefield, R. (2005). "The effect of supervisory leadership style on group level safety climate in the Australian construction industry." *Proc., QUT Research Week Int. Conf.*, A. C. Sidewell, ed., Queensland Univ. of Technology, Brisbane, Australia.

Linstone, H. A., and Turoff, M., eds. (1975). *The Delphi method: Techniques and applications*, Addison-Wesley, Reading, Mass.

MacCollum, D. V. (1993). *Crane hazards and their prevention*, American Society of Safety Engineers, Des Plaines, Ill.

McDonald, N., and Hrymak, V. (2002). "Safety behavior in the construction sector." *Res. Rep.*, Occupational Safety and Health Institute of Ireland, Dublin, Ireland.

Molenaar, K., Brown, H., Caile, S., and Smith, R. (2002). "Corporate culture: A study of firms with outstanding construction safety." *Prof.*

Saf., 47(7), 18–27.

Neitzel, R. L., Seixas, N. S., and Ren, K. K. (2001). "A review of crane safety in the construction industry." *Appl. Occup. Environ. Hyg.*, 16(12), 1106–1117.

Ng, S. T., Cheng, K. P., and Skitmore, R. M. (2005). "A framework for evaluating the safety performance of construction contractors." *Build. Environ.*, 40(10), 1347–1355.

Nunnally, S. W. (2000). *Managing construction equipment*, 2nd Ed., Prentice-Hall, Upper Saddle River, N.J.

Peurifoy, R. L., Schexnayder, C. J., and Shapira, A. (2006). *Construction planning, equipment, and methods*, 7th Ed., McGraw-Hill, Boston.

Saaty, T. L. (1980). *The analytic hierarchy process*, McGraw-Hill, London.

Shapira, A., and Glascock, J. D. (1996). "Culture of using mobile cranes for building construction." *J. Constr. Eng. Manage.*, 122(4), 298–307.

Shapira, A., Lucko, G., and Schexnayder, C. J. (2007). "Cranes for building construction projects." *J. Constr. Eng. Manage.*, 133(9), 690–700.

Shapira, A., and Lyachin, B. (2004). "Development of indices for safety risk evaluation of construction sites with tower cranes. Part I: Detection and analysis of safety hazards." *Res. Rep. No. 017-740*, National Building Research Institute, Technion, Haifa, Israel.

Shapira, A., Rosenfeld, Y., and Mizrachi, I. (2008). "Vision system for tower cranes." *J. Constr. Eng. Manage.*, 134(5), 320–332.

Shapira, A., and Simcha, M. (2005). "Development of indices for safety risk evaluation of construction sites with tower cranes. Part II: Weighting of safety hazards and methodology for risk-scales development." *Res. Rep. No. 017-743*, National Building Research Institute, Technion, Haifa, Israel.

Shapiro, H. I., Shapiro, J. P., and Shapiro, L. K. (2000). *Cranes and derricks*, 3rd Ed., McGraw-Hill, New York.

Shepherd, G. W., Kahler, R. J., and Cross, J. (2000). "Crane fatalities—A taxonomic analysis." *Safety Sci.*, 36(2), 83–93.

Shiffler, D. A. (2006). "Crane city." *American Cranes & Transport*, 2(12), 21–25.

Skinner, H., Watson, T., Dunkley, B., and Blackmore, P. (2006). *Tower crane stability, CIRIA C654*, CIRIA, London.

St. John Holt, A. (2001). *Principles of construction safety*, Blackwell Science, Oxford, U.K.

Suruda, A., Liu, D., Egger, M., and Lillquist, D. (1999). "Fatal injuries in the United States construction industry involving cranes 1984–1994." *J. Occup. Environ. Med.*, 41(12), 1052–1058.

"Tower manufactures to issue structural safety guidance after storm damage." (2000). *Cranes Today*, 304, 7.

Yoon, K. P., and Hwang, C.-L. (1995). *Multiple attribute decision making: An introduction*, Sage, Thousand Oaks, Calif.

Yow, P., Rooth, R., and Fry, K. (2000). "Crane accidents 1997–1999." *Rep. of the Crane Unit of the Div. of Occupational Safety and Health*, California Department of Industrial Relations, ⟨www.dir.ca.gov/dosh/CraneAccidentReport.html⟩.

J. Constr. Eng. Manage., 2009, 135(1): 24-33