Automation in Construction 49 (2015) 250–261

Contents lists available at ScienceDirect

Automation in Construction

journal homepage: www.elsevier.com/locate/autcon

Geotechnical and safety protective equipment planning using range point cloud data and rule checking in building information modeling

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ARTICLE INFO

Article history:
Received 15 March 2014
Received in revised form 30 July 2014
Accepted 5 September 2014
Available online 22 September 2014

Keywords:
3D range point clouds
As-built data collection and modeling
Building information modeling
Construction excavation and geotechnical work
Cave-in and fall hazards
Laser scanning and surveying
Rule checking
Safety best practices, regulations, rules and standards
Semi-automated safety assessment

ABSTRACT

After experiencing 806 fatalities in 2012, safety continues to be among the top concerns in the US construction industry. Among all construction operations, excavation is one of the most hazardous because of its inherent consequences from potential cave-ins, falls, and contacts of workers-on-foot with equipment or unknown objects. Current design, planning, and inspection of safety equipment at excavation sites is insufficient as it is still done manually, infrequently, time-consuming, and prone to human error. A new method is presented that semi-automatically identifies fall and cave-in hazards related to excavation pits and models, among other temporary geotechnical excavation objects, the required fall protection equipment. The approach first extracts relevant fall risk criteria from safety rules and regulations published by the Occupational Safety and Health Administration (OSHA) and applied in industry best practices. Three-dimensional (3D) range point clouds from the excavated pits are then collected to measure the geometrical properties of the pit. An algorithm extracts height information automatically to identify and locate fall hazards. The integration of geometric parameters with geotechnical and safety regulations finally results in a building information model (BIM) that includes the installation of safety equipment. An experimental field trial demonstrates the applicability of the developed method for successful use by practitioners in the industry.

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1. Introduction

Excavation is a fundamental construction activity and consequently excavation is ubiquitous for early success in a project. Unfortunately, it has also been recognized as one of the most hazardous construction activities, presenting serious threats for health and safety to all workers involved. Despite the availability of well-known and effective protective systems such as sloping, benching and shoring, excavation-related accidents continue to plague the construction industry [1]. The sad fact is that each year more than 30 US construction workers die in excavation [2] and many more die from falls from higher levels [3]. Although excavation may not be directly recognized as one of the leading causes of construction worker fatalities, some of the risky behavior is associated to the most severe outcome: death of a worker. Examples are worker being crush by cave-ins, personnel falling into deep excavation pits, or too close contact of workers-on-foot with equipment or other hazardous objects [4].

The degree of danger for a particular work is often measured by the number of injuries or fatalities occurred to a group of workers, usually over a period of 1 year [5]. Among all the hazards of excavation, cave-ins pose the greatest risk and are much more likely to result in worker fatalities than other excavation-related accidents [6]. From 2003 to 2011, 287 workers were killed due to cave-ins in the private US construction industry. Eighty-four percent of those fatalities happened during excavating or trenching tasks. Other potential hazards such as falls, contact with objects and equipment, and low oxygen levels might be present during excavation, in particular in confined spaces. Out of the 806 worker fatalities in the US in 2012, 290 or 36% were related to falls from height [7]. Unfortunately, lagging safety indicator data, such as statistics analyzed and provided after tragic events, does often not provide more details about the accident. This makes it very difficult to investigate the root cause or the site conditions of the event [8]. As these statistics indicate, safety in excavation remains a big problem requiring additional focus to be put on advanced safety prevention methods.

In 1971, the Occupational Safety and Health Administration (OSHA) issued its first standard related to excavation to protect construction workers from excavation hazards. Based on that, several amendments have been made to ameliorate worker protection and reduce injuries or fatalities. Construction companies may often apply their own, more stringent industrial best practices of safety and health. Providing education, training, and personal protective equipment (PPE) to workers in addition to safe work conditions, is the least essential method to create a safe work environment [9].

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http://dx.doi.org/10.1016/j.autcon.2014.09.002
0926-5805/Published by Elsevier B.V.

Although the previously mentioned statistics would have been significantly worse if safety standards and best practices had not been issued and provided, excavation-related accidents resulting in injuries and fatalities continue to occur. In the construction industry, the identification and assessment of critical safety issues often involves the experience and judgment of field personnel, such as safety inspectors. The OSHA standards require that a competent person should inspect excavations and the adjacent areas for possible cave-ins, failure of protective systems and equipment, and hazardous atmospheres on a daily basis [10]. However, the diversity of accidents and their repetitive nature may lead to the conclusion that proper inspection of construction sites is infrequent or often not accurately performed. Due to economic constraints, safety inspectors are absent when needed [6]. For these reasons, novel methods for the (semi-automated) identification and mitigation of potential safety and health risks related to excavation in construction are needed.

Effective implementation of technology in construction safety complements existing safety culture, its procedures and processes [9,10]. A semi-automated method is presented in this paper to identify the safety and health risks associated to falls in excavated pits. It follows existing approaches in geotechnical information modeling, parametric and rapid automated 3D data acquisition and modeling based approaches in construction research [11–17]. Risk related to falls from height is identified by utilizing laser scanning technology that measures the geometric parameters (e.g., depth value and slope ratio) of an excavated pit. Registration and cleaning of the point cloud are done manually although automated techniques exist today [13–17]. Once the 3D as-built conditions of the pit are analyzed, feature points are extracted that assist in creating a simplified 3D information model of the pit. Protective safety guardrail is then added to the model automatically using safety rule checking in building information modeling (BIM) [3].

This paper is organized as follows. Section 2 undertakes a review of the current status and needs in safety-related practices in excavation. The objectives and scope of the developed method are presented in Section 3. Section 4 highlights the technological contributions, foremost in gathering and analyzing the point cloud and use of safety rule checking. Section 5 then explains the algorithms to extract risk information and the modeling and visualization efforts. Experimental implementation and validation showing results are shown in Section 6. Finally, Section 7 draws the conclusions, explains the limitation, and discusses the future of the developed approach.

2. Background

2.1. The current status of safety in excavation and trenching

It is mandatory for the construction industry to provide a safe and healthy work environment [18]. To improve safety in construction excavation, several best practices have been installed that can be generally classified into three categories: (1) pre-excavation, (2) excavation, and (3) post-excavation. Pre-excavation specifies the procedures needed prior to the actual commencement of any digging activities. While excavation deals with safety during the activity, post-excavation stipulates processes needed after an excavation is completed. More detailed safety rules and inspection requirements are available for excavation. Many of these are accessible in OSHA's excavation standards, e.g., the identification of a competent person that understands the scope of inspection, potential hazards of excavations, and accordingly, protective systems that prevent accidents and protect the workforce [6].

The complex and dynamic nature of construction during excavation, however, makes safety inspections far more challenging than any task in the pre- and post-excavation categories. In fact, excavation is responsible to most of the related injuries and fatalities of the entire excavation process.

Site conditions during excavation are constantly changing, often throughout the day. This is the reason why, currently, safety inspections rely on frequent manual observations. As required by OSHA, a competent person's job is to inspect site conditions regularly. This is mostly a manual, labor-intensive, and potentially error-prone task. In addition, best practices are imperative to improve safety in excavation, but are currently not capable of ensuring the presence of an inspector on site and the accuracy of the inspection.

Much research has also been carried out in regards to injuries and fatalities in construction excavation. The main objective so far is to determine the root cause of an accident to later on improve safety culture and behavior. A study completed by the Center for Disease Control and Prevention (CDC) reviewed such statistical safety data [19]. It identified 542 fatalities associated with trenching and excavation between 1992 and 2001. Cave-ins accounted for 76% of those fatalities. The study also recommended to designate a competent person for conducting daily inspections during excavation operations, including all adjacent areas and protective systems. The study further noted that such individuals should be empowered with relevant safety information in order to take necessary and appropriate measures to protect workers [19]. Other statistics highlight the importance of safety related to geotechnical work: 13 out of 15 in 2012 cave-in related fatalities in construction happened when workers were excavating or trenching [7]. Another study [20] reviewed 44 case files of OSHA's fatal accident reports: 23 or more than half of the trench operations failed and were cited in conducting daily inspections by a competent person. Failures in hazard identification are often due to lack of a good safety culture, resulting in the oversight or absence of a competent person.

2.2. Need for (semi-)automated hazard identification processes and systems

The literature on safety statistics has been reviewed to find evidence on why accidents occur and how they can be prevented. Even though remarkable improvements in excavation and trenching safety have been successfully implemented in recent years, many rely on proper

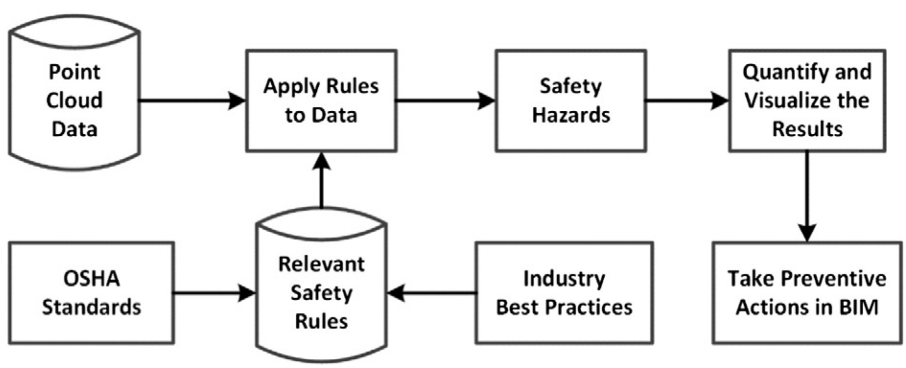

Fig. 1. Framework to identify, quantify, visualize, and mitigate hazards in excavation using 3D as-built and safety rule data.