Automatic Cave-in Safety Risk Identification in Construction Excavation

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ABSTRACT

Safety continues to be among the top issues in the construction industry after experiencing 738 fatalities in 2011. Among all construction operations, excavation is one of the most hazardous because of its inherent hazards with possible cave-ins, contact with objects and equipment, bad air, and so on. Up till today, most safety inspectors are still inspecting the site manually, making the inspection time-consuming and error-prone. This paper presents a method that automatically identifies cave-in safety risks in construction excavation. It first extracts relevant safety rules from OHSA standards and industrial best practices. Then, it collects a set of point cloud data of a construction site under excavation using laser scanning, registering and cleaning the point cloud data afterwards. Finally, it develops an automated identification algorithm based on those rules and applies the algorithm onto the data to identify potential cave-in risks by analyzing geometrical properties. An experimental trial is also conducted in this paper and results show that the method successfully identifies those cave-in risks. The presented method can actively monitor the fast changing situations of construction sites under excavation and help inspectors and project managers make good safety decisions, preventing accidents and fatalities.

INTRODUCTION

Excavation is a fundamental construction activity and consequently excavation is ubiquitous. Unfortunately, it has also been recognized as one of the most hazardous construction activities, presenting serious accidents to all workers involved. Excavation-related accidents continue to plague the construction industry, despite the availability of well-known and effective protective systems such as sloping, benching and shoring. The sad fact is that each year more than 30 construction workers died in excavation (CPWR, 2005).

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 (OSHA, 2002). A study completed by Center for Disease Control and Prevention (CDC) reviewed CFOI data identified 542 fatalities associated with trenching and excavation from 1992 to 2001 and found that cave-ins accounted for 76% of those fatalities (CDC, 2004). As the statistics indicate, safety in excavation remains a big problem and we need to take further actions to prevent them.
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. However, the diversity of accidents and their repetitive nature may result in the fact that proper inspection of construction sites is often not accurately performed or safety inspectors are absent when needed (Teizer, 2008). For these reasons, a method for the automated identification of construction excavation safety risks is needed.

Effective implementation of technology on assisting construction safety would complement existing safety procedures and make improvements (Pratt et. al 2001 and Teizer et. al, 2008). Such a method is presented in this paper to automatically identify cave-in safety risks in construction excavation by utilizing laser scanning technology. It first extracts relevant safety rules and regulations from OSHA standards and industrial best practices. Then, it collects a set of point cloud data of a construction site under excavation using laser scanning, registering and cleaning the point cloud data afterwards. Finally, it develops an automated identification algorithm based on those rules and applies the algorithm onto the data to identify potential cave-in risks by analyzing geometrical properties. The proposed method can actively monitor the jobsite and prevent accidents and fatalities.

This paper is organized as follows. Section 2 undertakes the review of the current status of construction excavation safety and the review of laser detection and ranging technology. Section 3 presents the scope and framework of this research. Section 4 discusses the excavation-related rules and regulations to be extracted from OSHA standards and other industrial best practices. Section 5 explicitly explains the safety risk identification algorithms in this paper. Section 6 demonstrates the implementing experiments as well as the results. Section 7 draws the conclusion and explains the limitations of this research.

BACKGROUND

The Current Status of Excavation Safety

It is mandatory for the construction industry to provide a safe and healthy work environment (Zhang et. al, 2013). The complex and dynamic nature of construction excavation, however, makes safety inspections during excavation very challenging. The conditions of the jobsite are almost changing every day at the operational level, needless to say those moving construction workers and equipment. Currently, excavation safety inspections rely on frequent manual observations by the competent person required by OSHA standards, making the inspection a labor-intensive and error-prone task. The most severe consequence of improper safety inspection is worker fatalities.

Research has also been carried out with regard to injuries and fatalities in construction excavation to reveal the causes of those accidents. A study by Deatherage and some other researchers reviewed 44 case files from OSHA inspections of fatal trench collapse and drew similar conclusion: Out of those 44 case files, 23 or 52% were cited as failure to conduct daily inspections of excavations by a competent person (Deatherage et. al, 2004). Failures in safety risk identification are often due to the oversight or absence of a competent person when inspecting hazards or executing safety practices is needed.
Limited research has been conducted on how to automatically identify excavation-related safety risks of a construction site. Chi and Caldas presented an automated image-based safety assessment method for earthmoving and surface mining activities (Chi and Caldas, 2012). But they primarily focused on the activities of loading, hauling and dumping but not on excavating itself and the method of image-based assessment they used does not carry enough information to analyze the geometrical properties of a construction site, which are the very critical part that best practices and OSHA standards rely on. The need for a system that can automatically identify excavation-related safety risks, therefore, still exists.

Laser Detection and Ranging Technology

Laser detection and ranging (LADAR, also known as laser scanning) is one of the technologies that have been broadly utilized for the research of construction, especially construction safety and health. Most recently, Marks et.al used laser scanner and gathered blind spot of several heavy equipment, to provide design suggestions that increase operator visibility (Marks et. al, 2013).

Selection of one particular technology depends on the application, density of data, accuracy, collection method, and frequency of updating (Teizer 2008, and Cheng et. al 2011). 3D terrestrial laser scanning is a promising geometric data collection technology for construction and measures the distance from the sensor to nearby objects, providing point cloud data with fast sampling rate and millimeter level accuracy (Tang et. al, 2009). Such data would enable the accurate geometric assessments of as-built jobsite conditions as to automatically and actively identify daily changing hazardous areas.

SCOPE AND FRAMEWORK

According to OSHA standards (OSHA 1926.650), three types of protective systems can be utilized to protect cave-in safety risks: sloping, shoring and shielding. This research focuses on automatically identifying cave-in safety risks with sloping protective system by analyzing geometric conditions of the site. The proposed framework of this research is shown in Figure 1.

![Figure 1 Framework for automatically identifying and visualizing excavation safety risks](image-url)
EXTRACTING RELATED SAFETY RULES

As previously stated, we explicitly focus on hazards of cave-in risks in excavation. OSHA standards (OSHA 1926 Subpart P Sub B) and several other best practices specify the maximum allowable slope (H: V) for different types of soil or rock when sloping protective system is used and Table 1 shows the details. Note that the maximum allowable slopes apply only if the excavation is 6.10 meter or less in depth. The construction manager should otherwise consult a professional engineer for the design of the protective system if the excavation depth is greater than 6.10 meter. Specific soil classifications are also available in OSHA standards (OSHA 1926 Subpart P Sub A). Construction managers should follow soil type C if the type of soil on a particular construction site is unknown.

Table 1 Maximum allowable slope with respect to different types of soil or rock

<table>
<thead>
<tr>
<th>Soil or rock type</th>
<th>Maximum allowable slope (α)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stable rock</td>
<td>Vertical (90°)</td>
</tr>
<tr>
<td>Soil type A</td>
<td>3/4:1 (53°)</td>
</tr>
<tr>
<td>Soil type B</td>
<td>1:1 (45°)</td>
</tr>
<tr>
<td>Soil type C</td>
<td>1 1/2:1 (34°)</td>
</tr>
</tbody>
</table>

APPLYING RULES ON DATA

This section presents detailed procedures for the process of applying safety rules and automatically identifying and visualizing cave-in safety risks. A flowchart of research methodology is illustrated in Figure 2. This research utilized Matlab™ to develop the algorithms for data processing.

Figure 2 Flowchart of automatically identifying and visualizing excavation safety risks

Data Preprocessing

Data preprocessing contains two processes: point cloud data registration and point cloud data cleaning. The point cloud data of as-built site conditions can be collected by utilizing a commercially-available laser scanner. It usually takes multiple scans of the construction site since it is hardly to get the scanning of the whole site by a single scan. The location of laser scanner will become the origin of local coordinate system for each scan and point clouds from each scan will be temporarily represented in their local coordinate system respectively. The registration process registers each scan of point cloud data into a global coordinate system, enabling the full information of the construction site.
The cleaning process generally removes unwanted data such as mixed pixels and points caused by moving objects prior to downstream process (Tang et. al, 2009). Depending on the algorithms, objects such as trees, telegraph poles and some other surrounding roads and buildings may also be part of the unwanted data. This process can be either performed on the level of individual scan or after all scans of point cloud data have been registered. The presented algorithm in this paper does not require or focus on the automation for registration or cleaning. So we will manually aid the registration and remove the unwanted data in this research. It takes about half an hour for the whole process with an experienced user.

**Building Occupancy Grid**

The registered and cleaned point cloud data will then be exported as a xyz file full of geometrical information. The geometrical information in the file is stored as an N x 3 matrix where N is the total number of points and the three columns represent X, Y and Z coordinates for each point respectively. Based on the geometrical information, we build up a three-dimensional occupancy grid along the X, Y, and Z axis by computing a bounding box of the dataset (Cheng and Teizer 2012, Teizer et. al 2007). The grid has multiple user-defined size cubic units called cells (or voxels, volume pixels) and range points falling within a cell’s coordinates are considered to be inside that particular cell. A cell with no inside range points is an empty cell and empty cells will not be processed in any downstream process of the algorithm, analyzing detailed geometrical properties of each cell. Using the methodology of building occupancy grid makes the algorithm computationally much cheaper since most (more than 90%) of the cells are empty and they will no longer be processes in future.

**Cave-in Risks**

The important two criteria we need to quantitatively measure and take into account are the depth of the excavation and the actual slope of soil on construction site as stated before. The algorithm computes and considers both factors to identify cave-in risks.

*Computing Depth of Cell*

It is clearly stipulated in OSHA regulation (OSHA 1926 Subpart P App B) that the computation of excavation depth is based on the height of the ground surface of the construction site. And the height of the ground surface can be computed by analyzing the geometrical properties of the construction site that ground surface usually enjoys the most dramatic horizontal density for nonempty cells. We can therefore accurately estimate the ground surface height by plotting the distribution of number of nonempty cells along the elevation. The elevation range contains the most nonempty cells is the one that ground surface exists and we can take the middle elevation within the range as the estimation for the height of the ground surface.

Once we have the height of the ground surface, we can easily compute the depth of each nonempty cell by: \(<\text{Depth of Cell}> = <\text{Z Minimum}> - \text{ground surface height}\).
**Computing Slope of Cell**

The slope of each nonempty cell can be computed by fitting a plane to all the range points within a cell and measuring the slope of the fitted plane. The method of fitting a plane applies only to cells with at least three non-collinear range points. Those cells usually share the most portions among all nonempty cells. Details for methods and algorithms of how to fit a plane to 3D points are not covered in this study. The normal vector of the fitting plane is considered as the normal vector for the cell and the slope of cell \( \theta \) can be therefore calculated by

\[
\theta = \arccos \left( \frac{\mathbf{N} \cdot \mathbf{Z}}{|\mathbf{N}| \times |\mathbf{Z}|} \right)
\]

where \( \mathbf{N} \) is the normal vector of the cell and \( \mathbf{Z} \) refers to Z axis.

**Identifying Cave-in Risks**

We apply the previously extracted rules to identify whether a cell has potential cave-in risks by considering both the depth of cell and the slope of cell. Notice that the maximum allowable slope \( \alpha \) is determined by the type of the soil on the construction site and it would be considered as 34º when the soil type is unknown. Figure 3 illustrates the algorithms for identifying cave-in risks in details. After running the algorithm, each nonempty cell with a fitting plane would be identified as either safe or hazardous and classified with particular hazardous type for visualization. Nonempty cells without a fitting plane cannot be identified.

**Visualizing Cave-in Risks**

The visualization of the above identified cave-in risks is straight forward and follows the rules below. Cells with excavation depth over 6.10 meter are identified hazardous and classified into type 1 with red color because the construction manager should consult a professional engineer to design the protective systems in this case. Cells with excavation depth between 1.52 meter and 6.10 meter and with slope over the maximum allowable slope \( \alpha \) are also identified hazardous and classified into...
type 2 with blue color because protective systems are needed for these areas. All other eligible cells are marked green for safe areas since they are either within 1.52 meter for excavation depth or they do not excel the maximum allowable slope. Empty cells will not be visualized.

EXPERIMENTS AND RESULTS

Data Collection

A construction site under excavation was selected to conduct the experiment. The size of the site was approximately 120m by 80m and the deepest part of the excavation was more than 8m. At the time of the experiment, the construction progress was almost at the end of excavation so protective systems had been used. As previously explained, four scans of data were collected by a commercially-available from four different locations to ensure the full geometric information of the site.

Data Preprocessing

By identifying approximate range points in different scans of point clouds, four scans of point cloud data were then manually registered in a global coordinate system. The registered point cloud data was also cleaned in manual effort to remove aforementioned noise such as mixed pixels and irrelevant surrounding areas. The view of the construction site after registration and cleaning is presented in Figure 4 and the dataset contained 7,771,131 as-built points. Four white circles in the figure indicate the location of the laser scan station for each scan.

Figure 4 View of the construction site after registration and cleaning

Building Occupancy Grid

We then built up a three-dimensional occupancy grid for the data, consisting of multiple cubic cells. Depending on the scale of the construction site and level of computational complexity, the size of cell was defined as 0.3m x 0.3m x 0.3m in this experiment, and it can be adjusted from case to case. A total number of 4,444,000 cells were constructed while only 125,013 of them are nonempty.
Identifying and Visualizing Cave-in Risks

The ground surface height of the construction site can be estimated by considering the elevation density of nonempty cells as shown in Figure 5. The second bar from the bottom has the highest density with almost 40,000 out of 125,013 nonempty cells. We can therefore estimate the ground surface height to be the middle elevation within the second bar as 19.95 meter. And the depth of each nonempty cell can be calculated by \(<\text{depth of cell}> = <\text{Z Minimum}> - \text{ground surface height}\).

![Figure 5 Distribution of nonempty cells by elevation](Image)

Another factor we need to consider is the slope of each nonempty cell, which can be computed by the method explained in previous section. Recall that the maximum allowable slope is determined by the type of soil according OSHA standards. The authors of this paper are not sure with type of soil on the construction site where this experiment was conducted, so the maximum slope follows that of soil type C with 34° as OSHA standards stipulated. Notice that the maximum slope is also set as a user defined input in the identifying algorithm and it can be adjusted by the user for different soil types on different construction sites. Then by running the algorithm, cave-in risks can be identified and classified into three categories: hazardous type 1, hazardous type 2, and safe. The first type of hazards represents cells which are over 6.10 meter. In this case, the construction manager should consult a professional engineer to design the protective systems. The second type of hazards represents cells which are between 1.52 meter and 6.10 meter with slope of cell greater than the maximum allowable slope. In this case, the construction manager does not have to consult a professional engineer but protective systems are still needed. For cells classified to be safe, the construction manager does not need to worry about them because they are either within 1.52 meter or between 1.52 meter and 6.10 meter with slope of cell smaller than the maximum allowable slope. Cells considered to be safe will be marked green in the visualization and cells of the first
and second hazard types will be marked red and blue respectively. Empty cells will not be visualized. Figure 6 shows the visualization of the outcomes for cave-in risks identification.

Figure 6 Visualization of cave-in risks identification outcomes

CONCLUSION

The presented method in this research automatically identifies and visualizes cave-in risks for construction excavation. As the outcome shows, it generates meaning figures to construction managers, plotting areas of different level of hazard with different colors. The potential contributions of this method are in two-fold: creation of realistic safety inspection map and reduction of manual efforts.

However, two main limitations need to be overcome in order to realize the full potential of the proposed method. First, this method does not apply to construction site with excavation depth over 6.10 meters. In other words, the construction managers cannot make use of the outcome generated by this method if there is some area marked red. They should consult a professional engineer to design the protective systems as required by OSHA standards. Second, the proposed method computes the depth of cell with reference to the level of the ground surface as specified by OSHA standards. A local reference within a particular range could be considered to generate more realistic outcomes. But much research will be needed to specify the range on regulation level.

REFERENCE


Minimize the risk of Limited Situational Awareness.” Journal of Computing in Civil Engineering, in press.


