Automation in Construction 65 (2016) 86–101

Contents lists available at ScienceDirect

Automation in Construction

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

Automated measurement of highway retaining wall displacements using terrestrial laser scanners

Pedram Oskouie [1], Burcin Becerik-Gerber *, Lucio Soibelman [2]

Sonny Astani Department of Civil and Environmental Engineering, University of Southern California, Los Angeles, CA, United States

ARTICLE INFO

Article history:
Received 24 April 2015
Received in revised form 7 December 2015
Accepted 28 December 2015
Available online 13 January 2016

Keywords:
Construction quality control
Remote sensing
Highway retaining walls
3D laser scanning
Point cloud processing
3D feature extraction

ABSTRACT

Highway retaining walls are continuously monitored during their construction to ensure the required performance criteria are met. Currently, inspection data are obtained manually by using geotechnical field instrumentations and surveying equipment. The data collection practice is often time-consuming, and erroneous. High precision and accuracy of laser scanners have made them valuable in construction, especially for structural health monitoring and change detection. This paper proposes a new method to (1) extract geometric features of highway retaining walls from the laser-scan data; and (2) use the extracted features as benchmarks for detecting wall displacements. The method is evaluated using Mechanically Stabilized Earth (MSE) walls, which are one of the most widely used highway retaining walls in the United States. Specifically, we investigated the hypothesis that the horizontal joints between the panels of an MSE wall could be used in point clouds to detect the wall's displacement with the required accuracy for condition assessment purposes. First, the proposed methodology was tested using the actual point cloud data of an MSE wall. The proposed feature extraction method was able to extract the horizontal joints with 94.26% accuracy. Then to test the generalizability of the method, we created 3D models of an MSE wall by using the wall's actual dimensions and geometric parameters. These models were used to examine the validity of the hypothesis for 36 laser scanner settings and 15 wall displacement scenarios. Laser scanner sensor parameters along with the 3D models were imported into a simulation environment to generate synthetic data to evaluate accuracy of the proposed method. The method was also tested with 3D models of two more types of MSE walls for a selected number of simulation scenarios. The results demonstrated that the proposed method is capable of measuring wall displacements with an average error of 0.9 mm.

1. Introduction

Wall displacements often challenge construction and maintenance of highway retaining walls. Excessive movements of walls could result in damages, such as cracks on a wall's facade, cracks on highway pavement, and breakage of facing panels. Mechanically Stabilized Earth (MSE) walls, since their introduction in 1970s, have been prevalently used as a promising form of highway retaining wall to stabilize steep slopes and to retain the soil below the freeway alignment where right-of-way constraints preclude the use of a sloped embankment. Their rapid, easy, and low-cost construction, as well as their capability in tolerating significant differential settlements compared to conventional concrete abutments have made them popular in the United States. Fig. 1 shows the cross section of a typical MSE wall.

Wall facing panels are used to hold the soil in position at the face of a wall. These panels are interlocked with soil reinforcements. The joints between panels are usually filled with a geotextile filter fabric to allow excessive water to exit and to prevent erosion of the soil through the joints [24]. The facing material influences settlement and the lateral displacement tolerance. Precast concrete panels are the most prevalent type of facing, not only due to their low cost and ease of installation, but also because they allow for aesthetically pleasing finishes. The panels have a minimum thickness of 140 mm and are in forms of cruciform, square, rectangular, diamond, or hexagonal geometry [4].

Stability of an MSE wall structure is inspected primarily from two perspectives of internal stability and external stability. External stability of a wall depends on the location of the project and the soil on which the wall is constructed. Vertical displacements (settlements) of a wall are attributed mainly to the external stability and are due to the consolidation of the soil beneath the wall. Consolidation of the soil depends on the soil type and level of moisture. Large settlements are expected at the beginning of a wall's construction since the soil experiences a new load, resulting in immediate consolidation. MSE walls can handle significantly more settlements compared to cast-in-place concrete walls. In addition, they can usually tolerate up to 1% differential settlement

* Corresponding author at: Sonny Astani Department of Civil and Environmental Engineering University of Southern California 3620 S. Vermont Avenue, KAP 224C Los Angeles, CA 90089-2531. Tel.: +1 213 740 4383; fax: +1 213 744 1426.

E-mail addresses: oskouie@usc.edu (P. Oskouie), becerik@usc.edu (B. Becerik-Gerber), soibelman@usc.edu (L. Soibelman).

[1] Tel.: +1 213 572 9373; fax: +1 213 744 1426.

[2] Tel.: +1 213 740 0609; fax: +1 213 744 1426.

http://dx.doi.org/10.1016/j.autcon.2015.12.023
0926-5805/

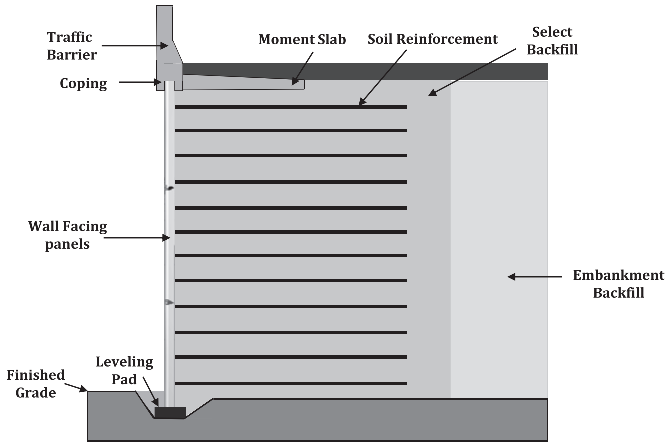

Fig. 1. Cross section profile of a typical MSE wall (Adapted from U.S. Department of Transportation [24]).

(100 mm settlement in 10 m for a square facing panel with joint width of 20 mm) [1]. MSE walls are monitored upon installation to ensure the settlement is finalized so that the subsequent construction activities can take place. For instance, items built on top of MSE walls, such as moment slabs, traffic barriers, and pavements, are not tolerant of settlement. Therefore, their construction takes place after the wall's settlement is over.

Internal stability is influenced by the select backfill's stability, excessive dynamic loads on the pavement and wall's crest, such as moving traffic or earthquakes. Horizontal movements (lateral displacements) of the wall are attributed essentially to the internal stability and they are due to the pullout of the soil reinforcement. Lateral displacement of soil results in sliding, over-turning, and eccentricity of an MSE wall [5,9]. These movements are generally observed as the wall is built. Limiting the lateral displacements to less than 50 mm prevents unacceptable settlements and damage of the surrounding structures and transportation infrastructure, such as pavements [2]. Displacements greater than the above mentioned thresholds could potentially result in critical damages that are detectable by visual inspection.

Various geotechnical tests, instrumentations, and surveying equipment have been used to study the stability and performance of MSE walls [18,33]. Inclinometers and total stations are the main instruments that are currently used in the industry for monitoring reinforced soil structures and retaining walls. Although geotechnical instrumentations are accurate in determining wall displacements, they are usually installed in boreholes or are fixed to on-site structural elements, requiring additional effort. Stability of an inclinometer is subject to external movements due to site conditions and has to be verified throughout the data collection period to avoid erroneous measurements. Moreover, geotechnical instruments are usually installed in specific locations of a construction site that are determined based on the site conditions to avoid potential conflicts; therefore, the collected data is limited to the selected sections of the project [14]. On the other hand, optical survey of point targets using total stations is time-consuming and the data are limited to the surveyed targets. Therefore, the process is not optimal for data collection of a wall with large length and height as scanning all points on a wall is not practical. Moreover, accurate and detailed modeling of the reinforced soil structures for studying and predicting their behavior requires data points throughout the structure. There is a need for a high-speed and comprehensive collection of data as well as an automated method for measuring the displacements of these structures with an improved accuracy compared to the conventional methods.

Laser scanning technology, also referred to as LiDAR systems (Light Detection and Ranging), captures a physical geometry by emitting near infrared light beams and generates millions of data points (known as a 3D point cloud). LiDAR systems are becoming industry standards for collecting data, especially for high budget infrastructure projects, such as transportation systems [11]. Although LiDAR equipment are more expensive compared to the other imaging systems, such as digital cameras, their accuracy makes them essentially desirable for large-size projects, such as highway infrastructure, where high risk and maintenance cost are at stake. Laser scanning technology has been successfully used by researchers in change detection for civil infrastructure projects. For example, for documenting ground deformation during urban excavation [34], changes and deformations of a rock face cliff [7], bridge inspection [35,36], evaluating the quality of point cloud as-is BIM models [10], and construction quality control [13,20,25]. To the best of our knowledge, these studies primarily focus on representing changes of a target as a whole and lack to distinctively assign changes to specific features within the target; therefore, it is difficult to know what features should be used as a benchmark to evaluate changes within the target over a period of time. Additionally, the current change detection approaches require accurate manual inputs of parameters and there is a need for an automated change detection technique.

In order to investigate the possibility of measuring highway retaining wall displacements using Terrestrial Laser Scanners (TLS), in this paper, we studied MSE walls, since they are the most widely used form of highway retaining walls in the United States [8]. The work takes horizontal joints between highway retaining walls' panels as benchmarks and provides displacement data for all the panels on the wall through a fully automated framework. The general methodology consists of two steps. First, an algorithm is introduced for extracting MSE wall facing panels' horizontal joints from a TLS generated point cloud. Next, the displacement of the wall is determined by comparing the extracted joint displacements. In this paper, an overview of recent literature on stability analysis of MSE walls, as well as current change detection techniques for measuring MSE wall displacement is provided. The proposed method for automated displacement measurement using laser scanners is described in the Methodology section. A real-life dataset is used to evaluate the performance of the feature extraction module. Then different laser scanning settings and wall movement scenarios are simulated to validate the method's robustness under various conditions. Lastly, a discussion and plan for future work are presented.

2. Methodology

In order to measure MSE wall displacements, we developed a framework for an automated laser scan-based feature extraction that uses geometric features on the wall as benchmarks to detect movements. The framework integrates a 3D object detection algorithm with signal processing techniques to extract horizontal joints from 3D point clouds. The framework was validated using real-life data, which represent one of the most common forms of MSE walls. The robustness of the proposed framework is evaluated by analyzing the accuracy in extracting horizontal joints from the wall's point cloud, as well as the accuracy in measuring the wall's displacements using the extracted joints. The generalizability of the framework is then evaluated using synthetic data from other types of MSE walls. The following sections describe the MSE wall point clouds' geometric features; explain the proposed framework for automated wall displacement measurement; examine the feature extraction accuracy using real-life data; and evaluate the framework's performance using simulation techniques.

2.1. MSE wall 3D point clouds and basic assumptions

Fig. 2 shows typical front, top, and section views of an MSE wall's point cloud. The large indentations in the top view are vertical joints and the small indentations are the panel ridges. The section view shows how the horizontal joints are outlined in the point cloud. The penetration of laser beams in the facing panels' ridges creates a change of thickness for the point cloud, which is visually evident in the section view. The vertical joints generally generate larger and wider