Integration of Construction As-Built Data via Laser Scanning with Geotechnical Monitoring of Urban Excavation

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Abstract: The demand for urban underground space has been increasing in the past decades to create living space and to avoid traffic congestion. A critical concern during the design and development of the underground space is the influence of construction-related ground movements on neighboring facilities and utilities. Currently, engineers can estimate ground movements using a combination of semiempirical methods and numerical model simulation. However, these advanced analyses require accurate as-built construction staging data, which most projects lack. The traditional approach of collecting construction-staging data is both labor intensive and time consuming. This paper explores the use of three-dimensional laser scanning technology to accurately capture construction activities during development of an urban excavation. The paper describes the planning, execution, and data processing phases of collecting accurate construction as-built staging information over a period of 4 months at an urban excavation site in Evanston, Ill. The resulting data provide an unprecedented level of detail on the as-built site conditions and provide much needed information to civil engineering disciplines involved in an urban excavation including construction management and structural and geotechnical engineering.

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Introduction

With new development, and increasingly more redevelopment, within urban areas there is a clear need to efficiently and safely develop underground space. A major concern when placing deep excavations in urban environments is the impact of construction-related ground movements on adjacent buildings and utilities. In practice, when designers are faced with an excavation where ground movements are a critical issue, they can estimate movements using semiempirical methods or results of numerical modeling. It is common to include a monitoring program during construction to record the ground movements and, in some cases, adjacent building movements. Ideally, these observations are used to control the construction process and update predictions of movements given the measured deformations at early stages of construction as illustrated in Fig. 1.

In the course of excavation projects, civil engineers rely heavily on construction field data to evaluate current excavation conditions and make necessary adjustments to the construction activities as needed. Often, such evaluations are done by applying field data to numerical models, especially when the complexity of analysis extends beyond the use of engineering judgment. Significant progress has been made in the development of automated systems to monitor ground deformations due to excavation activities. However, there is a lack of detailed records of the construction activities, excavation geometry, and as-built conditions. Currently available records are often manual, incomplete, and difficult to acquire. Without information about the corresponding excavation configuration, data on ground deformations are of very limited use. The engineer is unable to correlate the movements to the corresponding excavation stage. Among several engineering disciplines involved in a modern urban excavation project, construction is perhaps the weakest link. Most companies rely on hand sketches for staging information or limited surveying points to conduct their analyses. A system capable of gathering accurate as-built data in a timely manner would be highly beneficial for urban excavation and construction. One of the most promising technologies available currently is the use of three-dimensional (3D) laser scanning to capture construction staging information. The following sections outline the 3D laser scanning technology and describe a case study that employs this technology to collect accurate construction staging information for use by multiple disciplines, including construction, geotechnical, and structural engineering, involved in an urban excavation project.

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3D Laser Scanning Technology

Three-dimensional laser scanning (3DLS) is a relatively new technology that utilizes light detection and ranging (LIDAR) to produce accurate 3D representations of objects. It is similar to radio detection and ranging (RADAR), but it uses light to mea-

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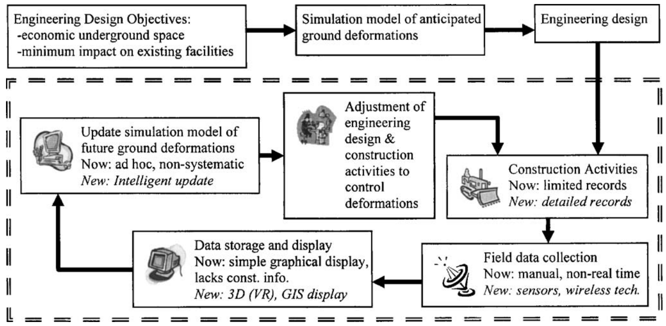

Fig. 1. Integrated framework for field monitoring and control of deformations for urban excavations

sure range or distance. A laser scanner consists of an emitting diode that produces a light source at a specific frequency. A mirror directs the laser beam horizontally and vertically towards the object as illustrated in Fig. 2. The surface of the object then reflects the laser beam. Using the principles of pulse time of flight, the distance to the object can be determined by the transit time, with a precision of ±4 mm. The result of a scan produces a collection of points in space, commonly known as "point clouds," which can be processed and combined into accurate 3D models.

The development of 3DLS in the last few years has made several laser scanning systems available for a wide range of applications. This technology has been used as a high-resolution 3D graphical model generator in historical buildings restoration, conservation, and artistic education of cultural patrimony, e.g., the digital Michelangelo project (Levoy et al. 2000), and character models for motion pictures and entertainment industries. In civil engineering, 3DLS is a relatively novel technology in the field of high definition surveying. Some studies were performed on implementing 3DLS for the construction industry (Belveau 1991; Akinci and Boukamp 2002; Kern 2002; Kim et al. 2002; Gordon et al. 2003). Volume calculation of a stockpile of construction materials using 3DLS has been conducted in a laboratory experiment at the National Institute of Standards and Technology (Stone et al. 2000).

Since these pilot experiments, more and more investigations about the applicability of 3DLS to the civil engineering domain were conducted. Examples are coastal bluff and landslide monitoring, and highway construction (Collins and Sitar 2005; Duffell and Rudrum 2005; Schaefer et al. 2005). However, most of these studies have focused on the static nature of three-dimensional models and today there is an even higher demand for analyzing the dynamic aspects of construction data. Today the technology has matured to a stage where it is possible to perform field scans in a relatively short time. Although equipment costs (both hardware and software) are still a constraint, more and more companies in the architecture/engineering/construction (A/E/C) industry are exploring new applications of 3DLS.

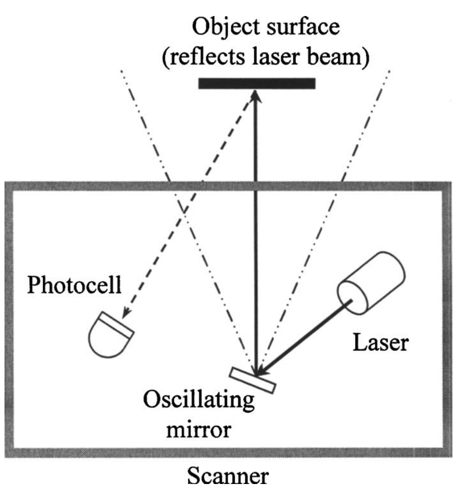

Fig. 2. Principle of laser scanning

Laser Scanner Used for Urban Excavations

This paper introduces the application of 3DLS to a number of civil engineering disciplines involved in an urban excavation. The paper presents a case study of field testing the 3DLS technology at an urban excavation site in the Chicago metro area. The scanner is used to acquire information about excavation geometry throughout construction to address issues related to geotechnical engineering, structures, and construction management. Issues include the actual volume excavated over a given period in order to assess pay items, excavated surface geometry, configuration of installed supports, and their relationship to measured movements using other instrumentation such as inclinometers and surface settlement points.

A Cyrax 2500 laser scanner (now rebranded as Leica HDS 2500) from Leica GeoSystems was used in this research. This scanner is equipped with an eye safe, green light, pulsed laser with a 40° by 40° field of view. Two rotating mirrors inside the scanner control the horizontal and vertical movement of the laser beam. A laptop with the Cyclone software (Leica GeoSystems) connects the scanner via a network crossover cable. This software controls the scanning operations and presents the collected scanning data in real time. The scanner is also equipped with a built-in digital camera which is very close to the scanning window. A digital image of the prospective scan area can be captured by this camera before scanning and the operator can select a desired scanning area of any rectangular size based on this image. The operator can also select the desired scan density of the laser points.

The positional accuracy of a single point is ±6 mm (1σ) at 1.5–50 m range. The distance accuracy is ±4 mm (1σ) over the same range as verified by Tucker (2002). The spot size of the laser beam is greater than 6 mm beyond a distance of 50 m and thus it is recommended that the scanning range be within 50 m. Outside this efficient range, the impact of the divergent laser beam on the scanning accuracy is considerable. In addition to the small beam size, the scanner provides adjustable scanning density to acquire the object details with 25 mm minimum point-to-point spacing at a distance of 50 m. The highest point resolution of the scanner is 1 million points with 1,000 points in both horizontal and vertical directions. Each of these points represents what would conventionally be considered a single survey point. Within a maximum $40° \times 40°$ scanner field of view at a given position the maximum number of equally spaced points, in a spherical coordinate system, is $1{,}000 \times 1{,}000$ points. This represents the maximum resolution that can be obtained in a single scan. The resolution of the scanned image can be reduced within this maximum field of view. Alternately, the resolution of a scanned image can be increased by decreasing the selected field of view (less than $40° \times 40°$) while still acquiring the full $1{,}000 \times 1{,}000$ points within that field of view. The resolution of a scan is a function of the scanning equipment, the available computer data acquisition

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and data manipulation systems, and the needs of the application of interest. The available resolution is expected to increase with the development of newer scanning equipment and faster computer systems.

The scanner is placed on a portable tripod-mounted system and can be operated by one person. Once the scanner is in place and connected to a laptop computer, the user simply orients the scanner towards the desired spot. The laser scanner scans a single scene view (called ScanWorld) automatically and captures a set of "point clouds." A single scan with a 1 million point resolution takes about 15 min to acquire. Each scan consists of point clouds and includes 3D coordinates of the points relative to the scanner position and the intensity value of each point. This intensity is affected by the surface material, the angle of incidence, and the distance of the object surface to the scanner.

A single scan restricted to the scanner field of view is insufficient for generating a three-dimensional model of an entire excavation. Multiple scans at different locations must be conducted in order to capture the entire site, whereby adjacent scans are overlapped. The points within the overlapped area are used to stitch individual scans together to form a 3D model as described in the following paragraphs.

The field phase of a laser scanning campaign consists of the acquisition of a set of individual scans that cover the excavation site of interest. Significant postprocessing effort is required to extract relevant information. The original scanned data is stored in a proprietary format readable by the manufacturer supplied software Cyclone. The data can be converted into pts, ptx, txt, xyz, or dxf file formats for use in other applications such as AutoCAD. In this paper, the writers mainly use Cyclone to process the scanned cloud point data. The available data processing software is versatile with numerous capabilities and the user will rarely have to manipulate raw data from the scanner. This is advantageous for routine engineering use. The following is a list of some primary postprocessing tasks:

1. *Stitching of scans:* In order to develop a scanned image of the entire excavation site it is necessary to stitch adjacent scans. In this research, an 8° overlapping angle between adjacent scans is adopted based on manufacturer's recommendation and field trials conducted by the writers to minimize stitching errors. The overlap zone covers one fifth of a $40° \times 40°$, 1 million point scan and contains about 200,000 points that are sufficient to perform necessary scanned image manipulation for stitching. Cyclone uses the algorithm called Iterative Closest Point (ICP) (Besl and McKay 1992) to stitch two adjacent scans. This algorithm requires the user to identify at least three pairs of corresponding (closest) points from the two point clouds to initiate the alignment process. By minimizing the sum of the squared distances of all the points [i.e., minimize the root mean square (RMS) error] within the overlap zone, the ICP is able to find the optimal alignment transformation between the two point clouds. The resulting stitched scan image is also a point cloud. Targets can be placed onsite within the overlap zones to improve the stitching process and reduce the errors. However, it was impractical to use such targets within an active excavation construction site.
2. *Triangulated Irregular Networks (TIN) meshes:* The cloud point can be converted to a mesh, called TIN mesh, so there are no overlapping triangles relative to the vertical direction. The minimum distance between any two points on the horizontal plane is a user defined value set to 1 mm in this paper. If two or more points are within this threshold, the point with the lowest elevation is kept to make the TIN mesh while the others are discarded. This TIN mesh can help the user reduce redundant points from the overlapping areas of stitched scans.
3. *Cross sections:* It is possible to slice the image along any desired plane orientation to obtain vertical cuts or sections of an excavation model to closely examine the terrain in 2D. A vertical cut plane can be set up at any desired position to slice the terrain mesh resulting in a polyline defined by the intersection of the plane with the terrain mesh. A 2D terrain profile is automatically generated and the z coordinates of the points on this profile polyline represent the excavated depths relative to the defined reference ground surface. This function is a built-in (automated) feature within Cyclone software.
4. *Volume calculations:* The volume is obtained by integrating the vertical distance between the terrain mesh to a reference surface, which can be a second terrain mesh or a reference plane defined by the user. This function is also a built-in feature within Cyclone software.

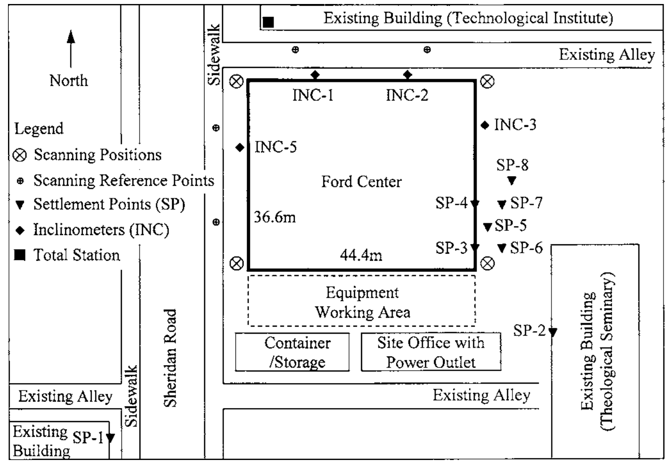

Fig. 3. Scanning and surveying site layout

Ford Center Excavation Case Study

The Northwestern University Ford Motor Company Engineering Design Center project is a six-story building (two underground) with 25,600 m^2 floor area and is located in the heart of the Northwestern University campus. Construction started in November 2003. With an approximate dimension of $44.4 \text{ m} \times 36.6 \text{ m}$ (length $\times$ width) and a maximum depth of 8 m below ground surface, a sheet pile wall supporting the excavation site was installed in mid-January 2004. The excavation activities lasted until mid-May 2004. During the entire excavation period, a laser scanner was utilized weekly to perform 3D field scanning.

More traditional instrumentation were also employed to monitor ground deformation as shown in Fig. 3. A total station was installed on the top of the existing Technological Institute Building. Four inclinometers were installed behind sheet pile walls, one on the west side, two on the north side, and the other one on the east side. Six settlement points were also set up on the west side near the southeast corner, two were sitting on the sheet pile wall, and the other four were on the ground. Two additional points were marked on the far southwest and southeast neighboring buildings serving as surveying control points.

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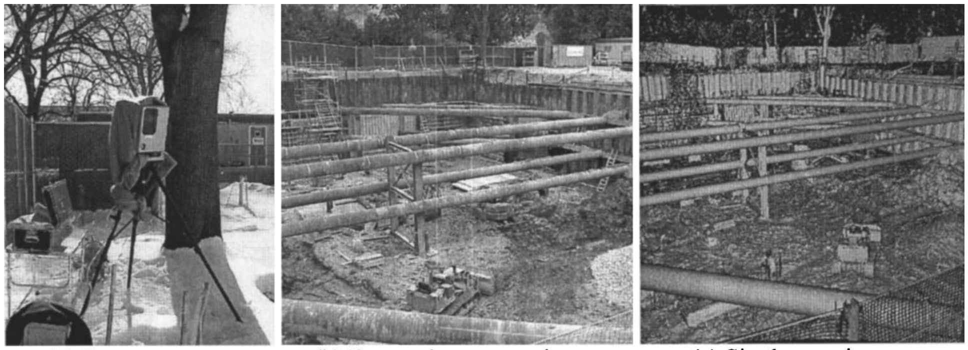

Fig. 4. Scanner setup for scan session 1 on January 30, 2004 and single scan image from scan session 13 on May 7, 2004

Scanning Logistics

Preplanning for site scanning is required to study possible scanning locations and coordinate with on-site construction management. These locations must provide views that are as unobstructed and as clear as possible while at the same time the scanner should be positioned in safe and nonconflicting areas so as not to interfere with ongoing construction. Fig. 3 shows the main scanning position areas near the four corners of the excavation site and outside the excavated area. The four corners were adopted because they minimally interfered with the workflow, provided more personnel safety, and a minimum number of scans were needed to cover the whole site. Note that the scanner does not need to stay in the same exact position for repeated scanning. The actual scanning position and the number of scans to cover the whole site depend highly on the surface geometry and site activities during scanning. Scanning reference points were also selected to facilitate image referencing and the verification of accuracy in the scanned images.

Fig. 4 illustrates the scanner setup and the resulting single scan image (viewed as mesh image) at the Ford Center construction site. The image is a 3D to scale geometric rendering of the site. It is possible to view the scanned image from any perspective and zoom in/out on particular areas to highlight relevant site features.

A total of 13 scan sessions were conducted during a 4-month excavation period. Table 1 shows the scanning dates and the number of single scans in each scan session. Note that the number of scans needed to cover the whole site varies between 8 and 17 for a single scan session. Fewer scans are needed if the site is relatively uncluttered by construction equipment or materials. The first and the last two scan sessions which were at the beginning and near the end of excavation were conducted from two opposite scanning positions [northeast (NE) and southeast (SE) corners for Session 1, NE and northwest (NW) corners for Sessions 12 and 13], whereby four single scans for each position were sufficient to develop a good 3D model.

Through this extensive scanning campaign, several important observations are made:

1. Site preparation is key to safe and efficient scanning. The scanner operator needs to coordinate scanning tasks with site manager during the prescanning stage. By understanding the site layout, equipment working areas, and moving paths, the user can organize several safe areas for conducting scans which will not interfere with the working equipment to avoid accidents. The user also needs to consider the fewest scanning positions which can capture the whole site with the fewest scans to make scanning efficient.
2. A unified coordinate system is needed for the integration of laser scanning and traditional surveying. Using scanning targets on site can help the user create a consistent coordinate system which applies to different scan sessions.
3. Objects, such as equipment, material and personnel, and site terrain in the construction site can block certain scans, resulting in missing data in the 3D model. Multiple scans from various angles and locations at different times become necessary. Static materials and equipment tend to create black holes after being removed from the scanned surface. These black holes can later be digitally filled up with meshes.
4. All scanning was performed from the outside perimeter of the open excavation in order to avoid interfering with ongoing excavation and construction activities. It was possible to cover the entire excavation area with minimal line of sight obstruction by scanning from several locations. In addition, scanning from outside the excavation poses less of a safety hazard to the scanning equipment and crew without compromising the accuracy of the scanned images. If the excavation is covered, it might be necessary to place the scanner within the excavation work area and more scans will be needed.
5. As shown in Fig. 4(a) and the temperature column in Table 1, scanning was successfully performed in January and February at sub-zero temperatures. Weather protection, such as warming blankets and tents, which do not block the scan-

Table 1. Summary of Scan Sessions at Ford Center Excavation

Scan session	Date	Number of scans	Average daytime temperature (°C)	Weather condition
1	January 30, 2004	8	−17.0	Sunny
2	February 4, 2004	14	−6.5	Sunny
3	February 11, 2004	17	−4.0	Cloudy
4	February 18, 2004	17	−1.5	Cloudy
5	February 27, 2004	16	2.5	Sunny
6	March 3, 2004	11	5.5	Cloudy
7	March 12, 2004	16	−4.5	Cloudy
8	March 26, 2004	15	13.0	Sunny
9	April 2, 2004	15	7.0	Sunny
10	April 9, 2004	17	7.0	Sunny
11	April 14, 2004	14	9.0	Sunny
12	May 3, 2004	8	5.5	Cloudy
13	May 7, 2004	8	10.5	Sunny

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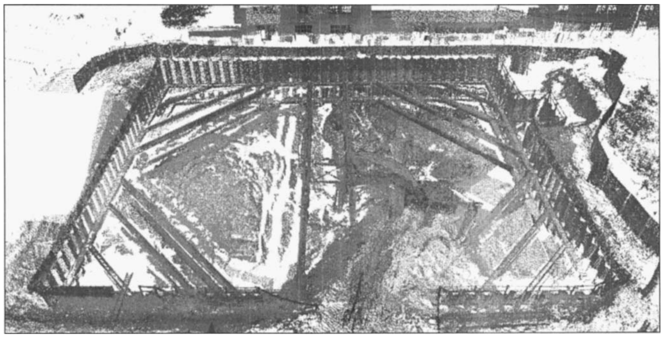

Fig. 5. Stitched, unfiltered, 3D point cloud model after registration, scan session 11

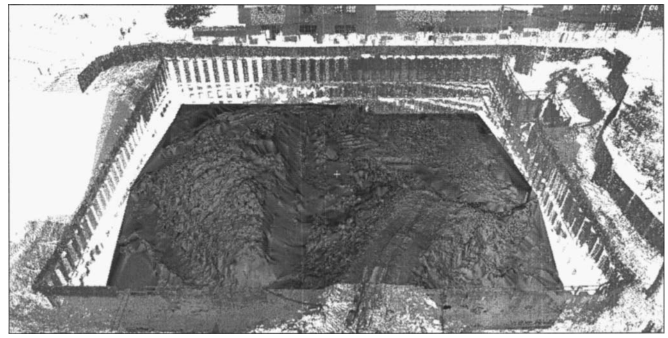

Fig. 6. Terrain TIN mesh created, scan session 11

ner's view, are necessary for winter scans to protect both the equipment and personnel as the scanner is certified to operate in 0 to 40°C temperature range.

Data Processing and Analysis

Multiple scans from a single scan session can be combined into a single 3D model through scan registration, data filtering and modeling. For generating a 3D model several scanning targets outside the excavation pit serve as control points while edges from nonmoving construction equipment or materials serve as reference points. The overlapping areas from all ScanWorlds are stitched (or *registered*) together to generate a single, to scale 3D point cloud model. From this registered ScanWorld, several copies (or ModelSpaces) can be developed for further manipulation and/or modeling purposes. Fig. 5 illustrates the result of a stitched model (combined scanned images) of the entire excavation. This 3D model provides high precision dimensions needed for engineering analyses. The accuracy of a 3D laser scanning model depends on the scanning distance and angle, the diameter of the laser beam, the point cloud spacing specified by the user and registration and stitching.

During the point cloud registration process the RMS error is used to represent the overlapping accuracy between two 3D point clouds (Besl and McKay 1992). By picking at least three pairs of constraint points from the overlapping area, the ICP algorithm (Besl and McKay 1992) is able to iteratively minimize the sum of the squared distances of the overlapping points and find the optimal alignment transformation between these two point clouds. User's skills in picking constraint points will directly influence the accuracy of a combined (or stitched) 3D model. Several factors affect the matching accuracy including the following:

1. The presence of moving objects (personnel, equipment, active soil excavation) in the overlap zones;
2. Adjacent scans with different point spacing: some excavation areas were blocked by large berms and additional scans were taken from other locations to cover the hidden areas with higher point density than the majority of the other scans during a given scan session; and
3. Scans from opposite sides of the excavation were sometimes necessary due to limited site access to scanning positions around the excavation perimeter as some of the scanning positions shown in Fig. 3 were inaccessible during some of the scan sessions.

The RMS errors in the 13 scan sessions vary from 4 to 19 mm with 75.6% of overall constraints having RMS errors less than 10 mm, and only 24.4% of constraints are within the 11–19 mm error window. Spot checks of known dimensions within the stitched scans are made. For example the diameters of two types of pipe struts, 0.61 m (24 in.) and 0.66 m (26 in.), existing in the 13 scan sessions are determined from the scans. The measurements are 0.594–0.633 m (average=0.613 m) for 0.61-m-diameter struts and 0.661–0.675 m (average=0.666 m) for 0.66-m-diameter struts and are very close to the known pipe strut dimensions.

After the registration of original scans the 3D model which consists of raw point clouds can be further manipulated for different purposes. Noise resulting from moving objects needs to be deleted before using these 3D point clouds for modeling and raw point filtering. The purpose of raw point filtering is to separate objects into different groups and layers for further processing. In this case study, at least four different groups are filtered from the original point clouds which include terrain within the excavation footprint, bracing, sheet piles, and surrounding ground and structures. This point filtering process can help in managing the objects easily and generating appropriate models for further analysis. For example, the points filtered from the terrain surface can be converted to a TIN mesh as shown in Fig. 6. This TIN mesh is developed with contiguous triangles in which no two vertices share the same X and Y coordinates, and no two triangles overlap along the vertical axis. It can provide useful representations for many kinds of field measurements. For example, a vertical cut plane can be placed slicing the terrain mesh to generate specific terrain profiles. The excavation depths at selected positions can then be automatically measured from the profile and the defined horizontal ground line. The accuracy of these depths is controlled by the accuracy of the individual scans (~6 mm), stitched model of the entire excavation (RMS value), and selected reference ground plane/line. Fig. 7 shows an excavation profile through the middle of the excavation site. However, an independent check of the accuracy of these specific estimates is not made.

In order to manipulate the models across all 13 scan sessions a unique coordinate system (UCS) is created. In this study, thousands of points from the wall of the adjacent Technological Institute Building in the first scan session are used to generate two reference planes that are normal to each other and the ground. From the normal lines of these two vertical planes, the x and y axis of the UCS are well defined. In addition, the existing building that appeared in each scan session also served as a useful georeferencing object from which the defined UCS can be transferred to the following scan sessions through the registration process. The UCS is the key to monitor a dynamic excavation site. It is necessary that preplanning of the scanning campaign should include the detailed georeferencing layout for the UCS. A suc-

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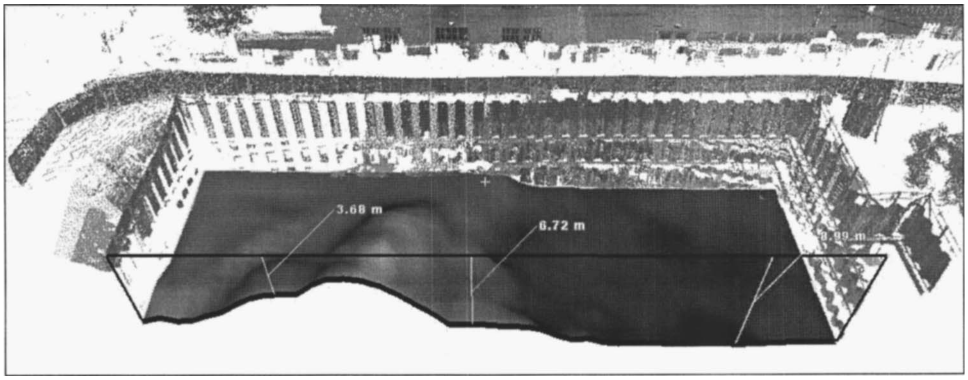

Fig. 7. Excavation profile, scan session 11

cessful UCS not only ties different scan sessions together but also integrates the scanning data with the measurements from other surveying tools or methods.

Use of Laser Scan Images in Construction Management

The 3D terrain models provide accurate excavation sequence over time. This accurate as-built construction sequence provides project managers with high fidelity data to track construction activities. For example, a horizontal reference plane can be set above the initial scan model. The volume of excavated material can be computed automatically by integrating the distance between the plane and the terrain surface. By comparing the volume of two terrain models the difference shows the excavated volume between these two scanning dates. Table 2 shows the cumulative excavated volume based on the horizontal reference plane and the excavated volume in the interval of two scanning sessions. This volume information provides timely and accurate excavation progress data and can become the payment basis for the excavation activity. Another horizontal reference plane can also be set at the planned depth of the excavation to calculate the remaining material volume to be removed. The excavation contractor can easily estimate the loose/bank ratio of the soil from the number of dump trucks and the excavated bank volume (pay items). This information would benefit the contractor in arranging construction equipment for excavation planning. Other construction applications include project as-built archive for claims and dispute, lay down area analyses, and construction inspections. Furthermore, because of the capability to capture accurate 3D shapes of the excavation site at various construction stages, the construction sequence is significantly more transparent and accurate as compared to the information available in the textual description from the daily logs or reports. This capability provides other engineering disciplines, such as geotechnical engineers, assessment of the impact of construction activities more precisely; thereby, project management teams can develop mitigating measures to reduce the construction impacts and risks. For contractors, accurate 3D excavation data also provide valuable information for equipment planning, site access, and layout management. From project management perspective, this may lead to less site congestion and safer jobsite.

Table 2. Excavation Volume between Scan Sessions

Scan session	Date	Excavated volume (m^3)	Cumulative excavated volume (m^3)
1	January 30, 2004	0	0
2	February 4, 2004	168.24	168.24
3	February 11, 2004	137.22	305.46
4	February 18, 2004	1,031.36	1,366.82
5	February 27, 2004	1,644.40	2,981.22
6	March 3, 2004	653.34	3,634.56
7	March 12, 2004	1,281.43	4,915.99
8	March 26, 2004	951.90	5,867.89
9	April 2, 2004	−223.26	5,644.63
10	April 9, 2004	1,077.02	6,721.65
11	April 14, 2004	559.52	7,281.17
12	May 3, 2004	4,005.28	11,286.45
13	May 7, 2004	387.00	11,673.45

Use of Laser Scan Images for Geotechnical and Structural Analysis

3DLS technology allows engineers to acquire excavation site geometry information in three dimensions. This information is almost absent from most excavation projects. Knowledge of excavation geometry is essential for correlating measured ground deformations using other instruments to specific construction activities. The 13 scan sessions provide detailed information on the changes in excavation terrain and the location of berms across the site as illustrated in the sequence of terrain images in Fig. 8. Berms are often used for equipment access and for reducing ground deformations due to soil removal and general stress relief within the excavation.

Fig. 9 shows how the laser scanned images can be used to understand measured deformation. The lateral deformations measured at inclinometer 1 (INC-1) on three separate dates are shown in Fig. 9, for which corresponding scans are also available as shown in the scan sessions (*j*), (*k*), and (*m*) in Fig. 8. From April 9 to April 14 significant excavation of soil occurred adjacent to the inclinometer but not elsewhere in the excavation. A small

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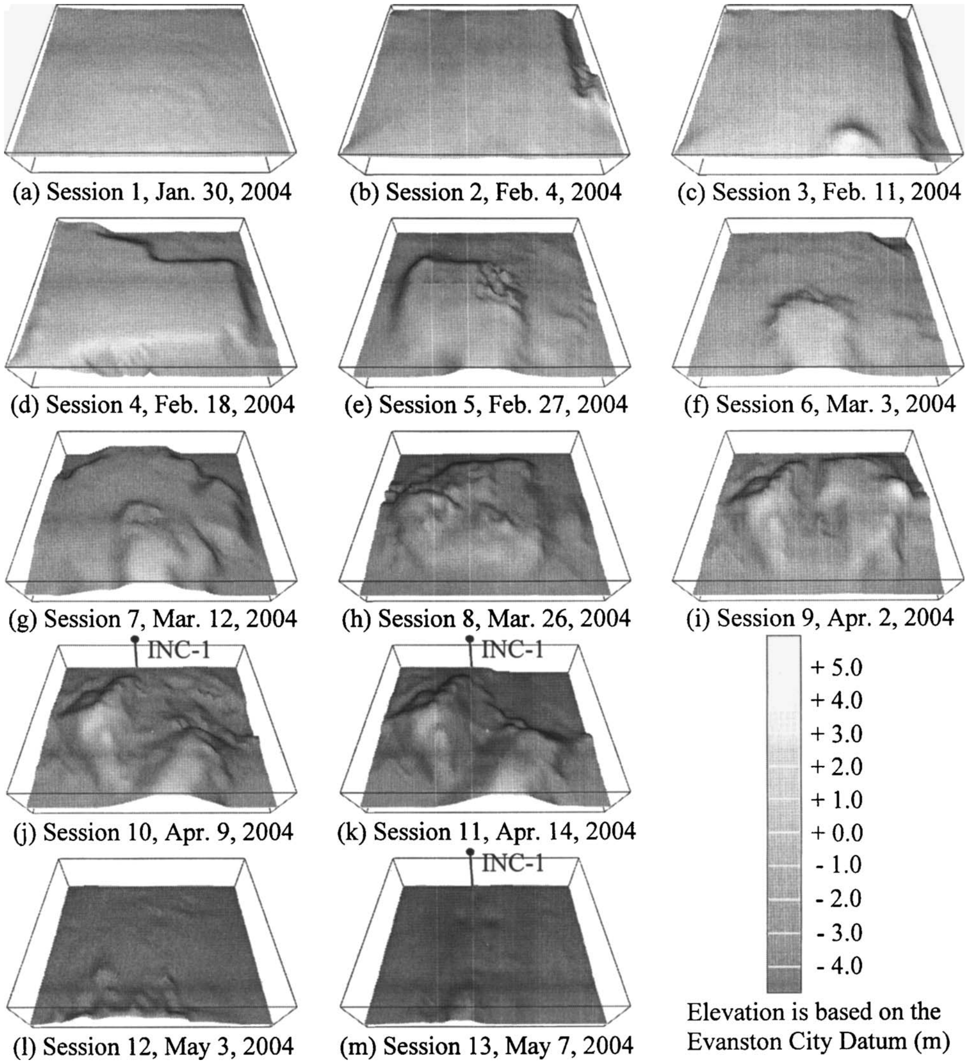

Fig. 8. Terrain geometry from 13 scan sessions

incremental lateral deformation is observed. From April 14 to May 7 the soil berms farther away from the location of the inclinometer are removed, but the inclinometer shows the lateral deformations have almost doubled. The incremental movement can be readily correlated to the 3D excavation activity within the excavation. This information is essential for the proper modeling of deformation due to deep excavations (Hashash et al. 2003).

The terrain mesh can be used to develop a finite element mesh for numerical modeling of the excavation process and its influences on ground deformations in the retained soil. Fig. 10 shows the TIN mesh used to develop a corresponding finite-element (FE) model (FEM). The FE model of the site prior to excavation is generated first using a FEM preprocessor. The user can specify the dimensions and size of the elements and density of the mesh in selected regions. Next, the 3D laser scan point data for a given excavation stage are compared with the node and element information of the FEM. Some elements in the base model located higher than the point data from the scan point data are deleted. As a result, the remaining elements represent the geometry of the excavation site. These 3D FEMs are essential to further the development of the SelfSim inverse analysis technique for deep excavations (Hashash et al. 2006).

Future Work

The writers believe that 3D laser scanning technology will encourage engineers and contractors to work closely together to not only enhance the quality of construction as-built data but also reduce the impact on neighboring infrastructure. The engineering and design objectives, such as costs and impact on existing facilities, will be better supported by having improved models to anticipate ground deformations. The prediction of deformations will be improved by accurate data from construction activities extracted by the use of 3D laser scanning. Instead of analyzing the model with only limited records of construction sequence and as-built data, detailed 3D records will give engineers new ways to corroborate their models and better predict the impact of construction activities and their sequence.

Conclusion

The need for usable space in urban areas has made urban excavation a common sight in cities around the world. Urban excava-

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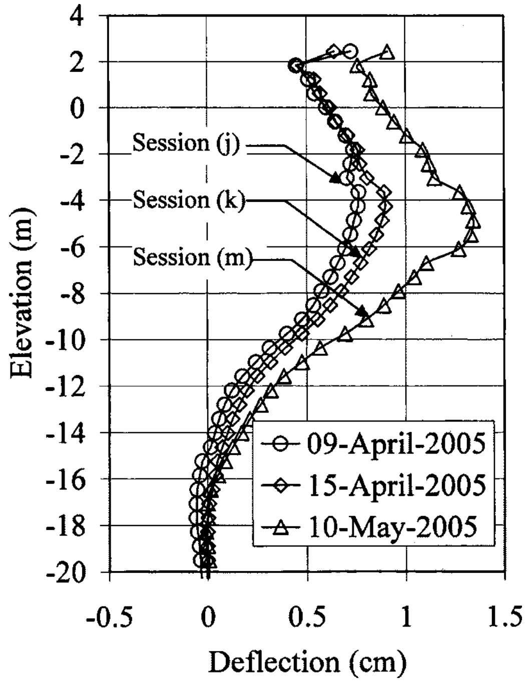

Fig. 9. Correlation of measured lateral wall deformations to excavation activity captured via laser scanning

tions pose a unique challenge to various engineering disciplines, including geotechnical, structural, and construction management. To control the impacts of urban excavation, engineers need to collect accurate construction data and collaborate among different engineering disciplines in order to control the impacts on nearby buildings and underground utility systems. The precision and promise of 3D laser scanning provide a new approach to collect high-fidelity data to support engineering analyses among various participants of urban excavation and construction. A 3DLS campaign at an excavation site near Chicago demonstrates the practicality of using this advanced technology on a routine basis on a construction project. Three-dimensional scanning technology provides timely and accurate as-built data that can be used for project management and control. These high-fidelity data also provide the much needed precision to other civil engineering disciplines, such as geotechnical and structural engineering, for better understanding and controlling of structural or ground deformations caused by construction activities.

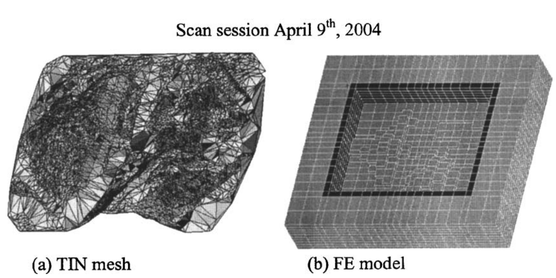

Fig. 10. Terrain mesh transformed and exported to develop finite-element mesh

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