Visual Measurement of Pile Movement for the Foundation Work using a High-Speed Line-Scan

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Abstract: When a construction company builds a high structure, many piles should be driven into the ground by a hammer whose weight is 7,000 Kg in order to make the ground under the structure safe and strong. So, it is essential to determine whether a pile is penetrated into the ground enough to support the weight of the structure since ground characteristics at different locations are different each other. This paper proposes a visual measurement system for pile rebound and penetration movement including vibration using a high-speed line-scan camera and a specially designed mark to recognize two-dimensional motion parameters of the mark using only a line-scan camera. A mark stacking white and black right-angled triangles is used for the measurement, and movement information for vertical distance, horizontal distance and rotational angle is determined simultaneously

Keywords: Visual Measurement, Line-Scan, Pile movement

1. INTRODUCTION

Visual measurement takes much attention since the measurement can be done by a non-contacting way. We can find many applications such as three-dimensional reconstruction and measurement of an object, posture determination of electronic components, and visual tracking of an object [1][2][3][4][5]. In most cases, two-dimensional video cameras are used for the measurement and overall processing is based on feature analysis in two-dimensional image planes. When dynamic motion of an object is included, however, the measurement performance – speed and accuracy - is constrained by image grabbing speed and imaging resolution of video cameras since blurring of images is happened and the image data is huge. So, in order to measure high-speed vibration characteristics of an object, there have been used two approaches using an acceleration sensor or a laser sensor.

Specifically, when a construction company builds a high structure, many piles - such as I-beam, H-beam and cylindrical-beam - should be driven into the ground by a hammer whose weight is 7,000 Kg in order to make the ground under the structure safe and strong. Therefore, it is essential to determine whether a pile is penetrated into the ground enough to support the weight of the structure since ground characteristics at different locations are different each other. Normally, when the penetration depth of the pile for ten hammerings is less than 4 millimeters, the constructor finishes the pile driving.

There have been proposed three approaches to measure the penetration and rebound movement of a pile. The first one is to draw a graph manually. That is, after a worker attaches a white sheet on the pile, the worker draws a horizontal line slowly during hammering job to drive the pile into the ground as shown in Fig. 1. The worker can obtain a manual graph only after finishing the dangerous hammering job. The second way is to measure the movement characteristics by attaching an accelerator sensor on the pile. Since the accelerator sensor outputs acceleration information of an object, we are able to determine the distance of penetration and rebound movement of the pile by integrating doubly the acceleration information. It requires a time-consuming process, however, to fix the acceleration sensor on the pile and the sensor data is noisy when horizontal vibrations of the pile are included. Another way to measure the distance of penetration and rebound movement of the pile is based on a speckle laser sensor [6]. Despite well-known laser sensors are used widely for measuring the distance between the target point and the laser sensor itself using time-of-flight concept, the speckle laser sensor are effective to measure the vertical movement of an object. Distance information of vertical movement can be obtained from the sensor data directly. The measurement resolution is 0.25 millimeters while its sampling rate is 8 milliseconds. So, it is not easy to observe the details of dynamic characteristic of the pile movement at impact instant between the pile and the hammer since the sampling time is long.

Fig. 1. Manual Measurement Example

In this paper, a visual measurement system for pile rebound and penetration movement including vibration is proposed by using a high-speed line-scan camera and a specially designed mark to recognize two-dimensional motion parameters of the mark using only a line-scan camera. A mark stacking white and black right-angled triangles is used for the measurement, and movement information for vertical distance, horizontal distance and rotational angle is determined simultaneously.

Especially, by adopting a line-scan CCD camera whose line rate is greater than 20 KHz, the measurement performance of dynamic characteristics of the pile at impact instant is improved. So, the developed visual measurement system is applied for a real penetration measurement system for building construction successfully.

Section 2 includes the structure of the mark and measurement equations for two-dimensional motion of the mark. Image processing algorithms are introduced in section 3 while section 4 shows experimental results for a spring system and a real pile penetration system.

2. MARK AND MEASUREMENT EQUATIONS

For the measurement of two-dimensional motion of a pile using a line-scan camera, we develop a mark using repetitive right-angled triangles as shown in Fig. 2. A line-scan camera grabs a line image by scanning from the top to the bottom of the mark attached on the pile.

Referring Fig. 3, it is possible to determine the coordinates of intersection points between the lines in the mark and the scan line of the line-scan camera. Here,

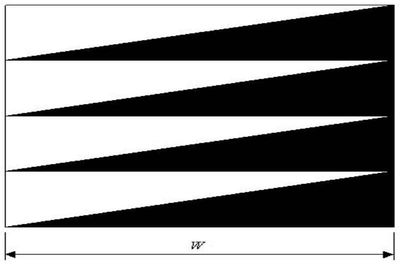

Fig. 2. Proposed Mark

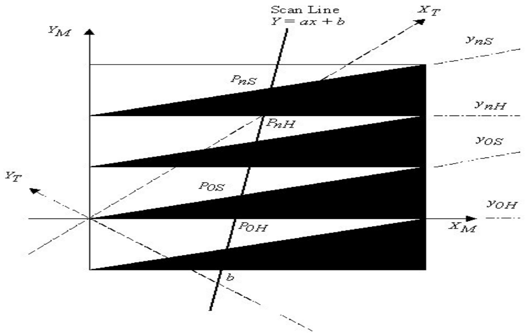

Fig. 3. Coordinate Frames for measurments

H : Height of the mark,
W : Width of the mark,
{M} : Reference coordinate for measurement,
{T} : Transformed coordinate for measurement.

The line expressed by $y = ax + b$ is the equation of the scan line of the line-scan CCD camera with respect to *{T}*. Then, if parameters of the line, a and b, are determined, the movement parameters for the mark can be calculated. When the rotational angle between two coordinate systems is 45 degrees, equations for the *n-th* horizontal and slanting line of the mark in *{T}* are expressed as follows, respectively.

$$y_{nH} = -x + n\sqrt{2}H \qquad (1)$$

$$y_{nS} = -\frac{1}{W+H}((W-H)x + n\sqrt{2}WH) \qquad (2)$$

Then, we can determine the coordinates of two intersection points between the scan line and the *n-th* horizontal and slanting line of the mark as follows, respectively.

$$P_{nH} = (\frac{n\sqrt{2}H - b}{a+1}, \frac{n\sqrt{2}aH + b}{a+1}) \qquad (3)$$

$$P_{nS} = (\frac{n\sqrt{2}WH - b(W+H)}{(a+1)W + (a-1)H}, \frac{n\sqrt{2}aWH + b(W-H)}{(a+1)W + (a-1)H}) \qquad (4)$$

Consequently, the ratio of the length of the *n-th* white band of the mark with respect to the length of *n-th* black band is determined while the line parameters, a and b, are extracted using the dimensionless length ratios as follows.

$$a = \frac{(L_n - L_m)W + \{L_m - L_n + (L_m+1)(L_n+1)(n-m)\}H}{(L_m - L_n)W + \{L_m - L_n + (L_m+1)(L_n+1)(n-m)\}H} \qquad (5)$$

$$b = \frac{\sqrt{2}WH\{m(L_m+1) - n(L_n+1)\}}{(L_m - L_n)W + \{L_m - L_n + (L_m+1)(L_n+1)(n-m)\}H} \qquad (6)$$

Here,

$$L_n = \frac{D(P_{(n+1)H}, P_{nS})}{D(P_{nS}, P_{nH})} = \frac{(a+1)W + (a-1)H}{n(1-a)H - \sqrt{2}b} - 1, \qquad (7)$$

$$L_m = \frac{D(P_{(m+1)H}, P_{mS})}{D(P_{mS}, P_{mH})} = \frac{(a+1)W + (a-1)H}{m(1-a)H - \sqrt{2}b} - 1. \qquad (8)$$

The *D(P, Q)* is Euclidian distance between two points *P* and *Q* in a plane. Based on the above concept and equations, the following relationship to determine the motion parameters of the mark using images from a line-scan camera is derived by using the image of single line shown in Fig. 4. The five edge points in the center of the image are used. Let $n = 0$ for a slanting line representing the nearest lower white-to-black edge with respect to the center of the image. At first, it can be found

$$L_0 = \frac{D_{1H} - D_{0S}}{D_{0S} - D_{0H}} \text{ and. } L_1 = \frac{D_{2H} - D_{1S}}{D_{1S} - D_{1H}}. \qquad (9)$$

Then,

$$a = \frac{(L_1 - L_0)W + \{L_0 - L_1 + (L_0+1)(L_1+1)\}H}{(L_0 - L_1)W + \{L_0 - L_1 + (L_0+1)(L_1+1)\}H}, \qquad (10)$$

$$b = \frac{-\sqrt{2}WH(L_1+1)}{(L_0 - L_1)W + \{L_0 - L_1 + (L_0+1)(L_1+1)\}H}. \qquad (11)$$

Next, we can determine the coordinate of the center point of the line-scan camera image by referring Fig. 3 as follows.

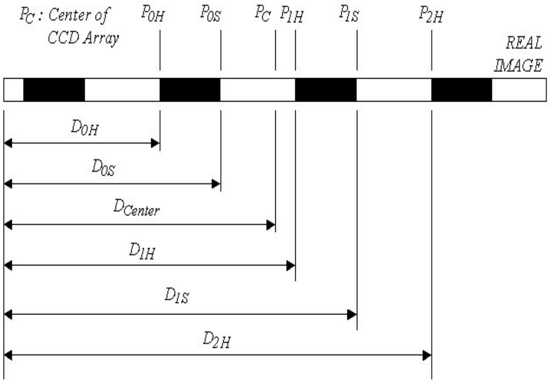

Fig. 4. Distances on a Real Image

$$P_C = RP_{1H} + (1-R)P_{0H} \tag{12}$$

where

$$R = \frac{D_{1H} - D_{center}}{D_{1H} - D_{0H}}. \tag{13}$$

Consequently,

$$P_C = (\frac{-b+\sqrt{2}HR}{a+1}, \frac{b+\sqrt{2}aHR}{a+1}) \tag{14}$$

since

$$P_{0H} = (\frac{-b}{a+1}, \frac{b}{a+1}) \tag{15}$$

and

$$P_{1H} = (\frac{-b+\sqrt{2}H}{a+1}, \frac{b+\sqrt{2}aH}{a+1}). \tag{16}$$

In order to endow the equations with the time, the initial coordinate of the center point and the coordinate of the center point at time t are described as follows.

$$P_{C0} = (\frac{-b_0+\sqrt{2}HR_0}{a_0+1}, \frac{b_0+\sqrt{2}a_0HR_0}{a_0+1}) \tag{17}$$

$$P_{Ct} = (\frac{-b_t+\sqrt{2}HR_t}{a_t+1}, \frac{b_t+\sqrt{2}a_tHR_t}{a_t+1}) \tag{18}$$

Finally, incremental quantities of linear and rotational movements with respect to initial location and orientation are determined by the following equations while

Δx_t : Linear movement perpendicular to scan line,

Δy_t : Linear movement parallel to scan line, and

$\Delta \theta_t$: Rotational movement with respect to the center of scan line.

That is, each quantity is described by the following two equations.

$$\begin{pmatrix} \Delta x_t \\ \Delta y_t \end{pmatrix} = \begin{pmatrix} \cos(\theta_0 - \pi/2) & \sin(\theta_0 - \pi/2) \\ -\sin(\theta_0 - \pi/2) & \cos(\theta_0 - \pi/2) \end{pmatrix} \cdot \left(P_{C0} - P_{Ct}\right)$$
$$= \begin{pmatrix} \sin\theta_0 & -\cos\theta_0 \\ \cos\theta_0 & \sin\theta_0 \end{pmatrix} \cdot \left(P_{C0} - P_{Ct}\right) \tag{19}$$

$$\Delta\theta_t = \tan^{-1} a_t - \tan^{-1} a_0 \tag{20}$$

The major advantage of the proposed approach is the fact that the slope and y-intercept of a scan line can be determined by dimensionless ratios between two lengths and there is no need for camera calibration.

3. IMAGE PROCESSING

Image processing algorithm is composed of three steps, threshold of gray-level images, edge detection and edge tracking.

The threshold is to obtain binary images from gray level images. When a zoom lens, whose magnification ratio is large, is adopted in order to increase the accuracy of measurement, the brightness of images is distorted by the zoom lens. That is, the brightness of boundary area of the images is darker than the brightness of central area. So, it should be overcome by using multiple windows for threshold. Fig. 5 shows an example for setting of multiple windows.

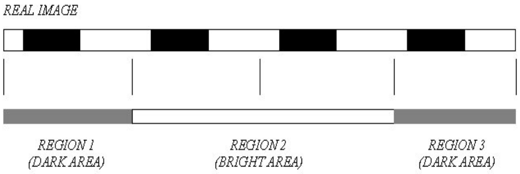

Fig. 5. Regions for Thresholding

Threshold values for binarization of three regions are determined independently [7]. Edge detection is to detect white-to-black edges and black-to-white edges after threshold in initial stage while edge tracking is following each edge point when the motion of a pile is beginning by hammering. After initial edges are extracted from a binary image, exact location of each edge is determined by differentiating images for a small region in the near of the initial edge point. The point whose differential value is greater than a threshold is determined as an edge point. For edge tracking, it is assumed that linear movement per sampling time is less than half of the height of a triangle in the mark. The new location of an edge is located by using binary search algorithm [8] in a bounded area based on the assumption.

4. EXPERIMENTS

The experimental system is composed of a high-speed line-scan CCD camera DALSA CL-P1 equipped with a zoom lens and a 866 MHz Pentium III personal computer including a frame grabber, Matrox Meteor-2/DIG, for digital cameras. The resolution of the camera is 4096 pixels per line while its line rate is set as 10 KHz. The height of a triangle in the mark is 40 mm while the width is 200 mm. There have been performed three kinds of experiment, the first for a mark attached on a motorized z-stage, the second for a mark attached on a spring system and the third for a mark of a real pile penetration system.

Fig. 6 shows an example image of 1000 lines obtained from the line-scan camera when the mark is at rest. A row means a scan-line. The left-hand side is the top of the mark while the right-hand side of the mark is the bottom of the mark. It is observed that the brightness condition is distorted by lens at the left-hand and right-hand boundary.

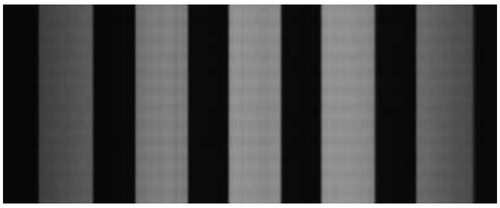

Fig. 6. Example Image

Since the sensitivity of CL-P1 line-scan camera is low, normal illumination condition under fluorescent lamps is too dark to process images correctly. So, two 500-watt halogen lamps are used for measurement. At outside of buildings, sunlight brighter than 5000 lux is sufficient to obtain good images to process.

As the first experiment, we measure the vertical movement of z-stage by moving the stage upward continuously in 0.5-millimeter step. The measured data is shown in Fig. 7. The horizontal axis represents the time for measurement from starting instant while the vertical axis shows the quantity of vertical movement. The maximum absolute values of measurement errors are less than 120 micrometers inside buildings. It is reasonable considering the natural vibration of buildings and vibration of the motorized z-stage for exact positioning.

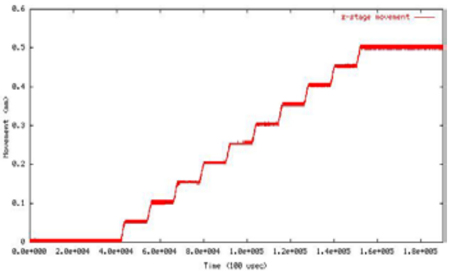

Fig. 7. Measurement for Z-stage Movement

In the evaluations for the first experiments, the result of measurements error is showing in Fig. 8. The x-axis is the numbers of try iterations and the y-axis is denoted by two values, one is real movement of z-stage and the other is the measured value by our system proposed. And Fig. 9. shows the standard deviation of the errors on Fig. 8. As the results of Fig. 8 and Fig. 9 for the evaluations, the proposed system shows the high precision and efficient performance.

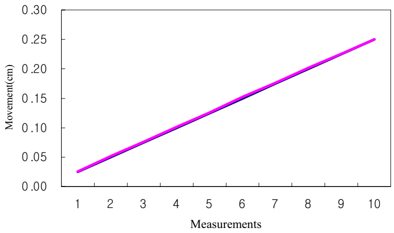

Fig. 8: Measurement Errors for Evaluation

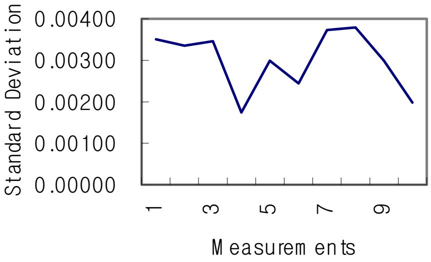

Fig. 9: Standard Deviation for Evaluation

Secondly, vertical movement of a plate fixed on a spring system is measured after a small hammer strikes the plate. The mark is attached on the plate. Several springs stretch the plate toward upper and lower directions. The measured data is shown in Fig. 8. The amplitude of vibration is reduced slowly by the damping characteristics of the spring system while the amplitude increases again when another shock is given to the spring system as shown in Fig. 10. Fig. 11 magnifying the circled interval in Fig. 11 shows that the measured data looks like a continuous data since its sampling rate is 10 KHz.

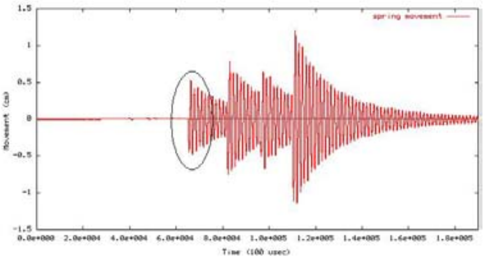

Fig. 10. Measurement for a Spring System

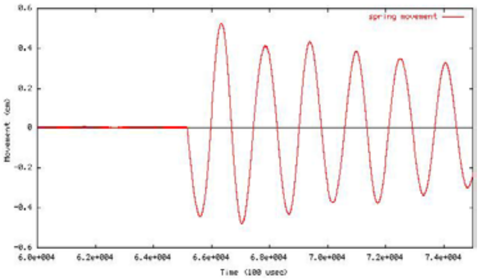

Fig. 11. Circled Region in Fig.10

Finally, we have obtained measurement data of vertical movement of a cylindrical pile under hammering in a real construction place. The weight of the hammer is 7000 Kg while initial distance between the hammer and the top of the cylindrical pile is 2 meters. Fig. 12 shows the measured data for 10 seconds, that is, 5 hammering intervals. The motion of rebound and penetration of a pile is shown clearly. Despite the rebound of the pile is observed at each impact, the pile is penetrated into the ground in global sense as shown in Fig. 12. The vertical movement of a pile after an impact is composed of four intervals as shown in Fig. 13. That is, those are penetration region at impact instant, rebound region after impact, settling region after rebound, and release region that the hammer is going upward for next impact.

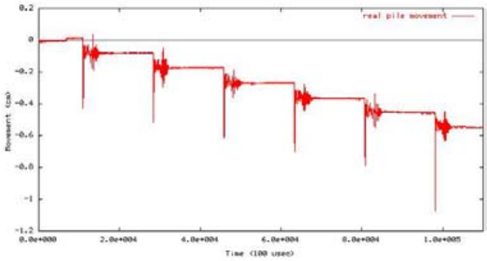

Fig. 12. Experimental Result of Measurement for a Real Pile Movement

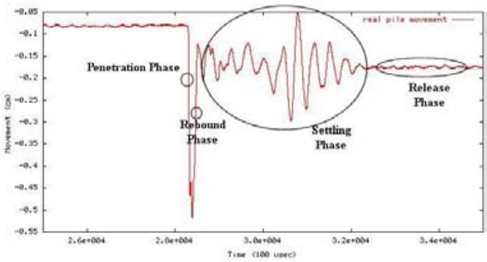

Fig. 13. Damping Characteristic of a Pile

The motion characteristic in settling phase is determined by the vibration of the pile itself and ground conditions. Since the sampling time for measurement is 100 microseconds, construction experts can investigate the dynamic characteristics of a pile in detail comparing with other equipments using laser sensors or accelerometers. It is noted that the sampling time of the equipment using laser sensors is 8 milliseconds [6]. Also, we can understand that the real penetration depth is shorter than the penetration depth at impact instant since repelling power from ground is very strong in finishing stage of pile penetration tasks.

In order to compare with our proposed method and a laser sensor method, Fig 14 and Fig 15 are showed the results of the pile penetration experiment in the same experimental environments. Despite the rebound of the pile is observed at each impact, the pile is penetrated into the ground in global sense as shown in Fig. 14. But the result of a laser sensor measurement showed that the precision measurement was not to measure as shown in Fig 15. The accuracy of a laser measurement is not better than the method of a digital line-scan camera. In this comparison, the sampling time for measurement is very important points, so the construction experts can investigate the dynamic characteristics of a pile in detail comparing with other equipments using laser sensors or accelerometers as shown in Fig 14 and Fig 15.

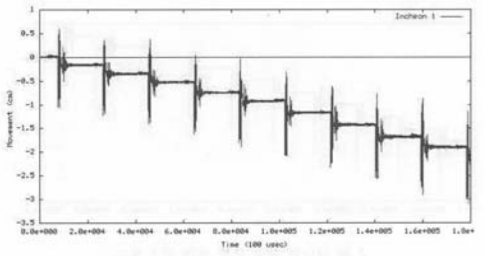

Fig. 14. Experimental Result for a site of work on ‘INCHEON LNG’

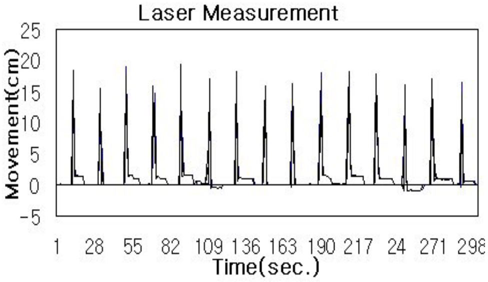

Fig. 15. Experimental Result for a site of work on ‘INCHEON LNG’ using laser sensors

5. CONCLUSIONS

We have been proposed a visual measurement system for observing pile rebound and penetration movement including vibration by adopting a high-speed line-scan camera and a specially designed mark to recognize two-dimensional motion parameters of the mark using only a line-scan camera. A mark stacking right-angled triangles is used for the measurement, and movement information for vertical distance, horizontal distance and rotational angle is determined simultaneously. Especially, by adopting a line-scan CCD camera whose line rate is 10 KHz, the measurement performance of dynamic characteristics of the pile at impact instant is improved dramatically comparing with the equipment using speckle laser sensors. And, its measuring accuracy is less than 120 micrometers under natural vibration of buildings and vibration of an electronic motor for exact positioning. Finally, the developed visual measurement system is applied for a real penetration measurement system for building construction successfully. It is expected that other mark stacking repetitive patterns can be used for measurement even though we have proposed an approach using right-angled triangles. The relationship between measurement accuracy and lens distortion will be investigated. Also, the possibility for sub-pixel analysis to enhance measurement accuracy will be examined.

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