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Development of Method for Evaluating and Visualizing 3-dimensional Deformation of Earth Retaining Wall for Excavation

Développement des méthodes d'évaluation et de visualisation de la déformation tridimensionnelle des murs de soutènement dans les excavations

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ABSTRACT: Monitoring of deformation of earth retaining wall for excavation is important in order to keep surrounding environment and structures safe during construction. However, there are some problems in monitoring of earth retaining walls. For example, it is difficult for the partial measurement by plum bobs to evaluate the overall behavior of the retaining walls, and the multipoint measurement using multi-element inclinometers tends to be expensive. In this paper, we developed a system to evaluate and visualize retaining wall as three-dimensional curved surface. The validity was confirmed by the simulation of the loading test on the model wall. In order to confirm the effectiveness of the proposed system to actual monitoring, we tried to apply the system to the on-site measurement. Furthermore, we proposed a method to conduct monitoring of retaining walls using this system and simple inclinometers.

RÉSUMÉ : Le contrôle de la déformation des murs de soutènement dans les excavations est important pour assurer la sécurité de l'environnement et des structures lors de la construction. Toutefois, le contrôle des murs de soutènement pose un certain nombre de problèmes. Il est par exemple difficile de procéder à des mesures partielles au fil à plomb pour évaluer le comportement général des murs de soutènement et les mesures multipoint à l'aide d'inclinomètres multiéléments sont plutôt onéreuses. Dans cet article, nous présentons un système d'évaluation et de visualisation des murs de soutènement sous forme d'une surface courbe tridimensionnelle. La validité du système a été confirmée par simulation d'un essai de charge sur la paroi du mur testé. Afin de vérifier l'efficacité du système proposé dans des conditions de contrôle réelles, nous avons tenté de l'appliquer lors de mesures sur le terrain. Nous proposons également une méthode de conduite du contrôle des murs de soutènement à l'aide de ce système et d'inclinomètres simples.

KEYWORDS: earth retaining wall, 3-dimensional deformation, cubic B-spline function, measurement, incline

1 INTRODUCTION

Monitoring of deformation of earth retaining wall for excavation is important in order to keep surrounding environment and structures safe during construction. However, there are some problems in monitoring of earth retaining walls. For example, it is difficult for the partial measurement by plum bobs to evaluate the overall behavior of the retaining walls, and the multipoint measurement using multi-element inclinometers tends to be expensive.

Considering these problems as backgrounds, we developed a system to evaluate and visualize retaining wall as three-dimensional curved surface. In this system, the cubic B-spline function is adopted as analytical technique, which is employed for describing shape of land as three-dimensional curved surface based on sets of data of the elevation altitude (Nonogaki et. al., 2008). We proposed a method to evaluate inclinometer data as surface without transforming incline into displacement. The validity and the adequacy was confirmed by loading test and field measurement. Furthermore, we seached the way two conduct measurement easily by using the proposed method.

2 EVALUATING AND VISUALIZING DEFORMATION OF RETAINING WALL IN 3-DIMENSIONAL SPACE

2.1 *Cubic B-spline function*

Figure 1 shows the 3-dimensional coordinate space for describing the deformation of the earth retaining wall. In this figure, x, y, and z axis means the direction of the retaining wall, the depth, and the direction toward which the wall deforms. The earth retaining wall is expressed as smooth and continuous surface by the following equation.

$$f(x,y)=z \tag{1}$$

In the cubic B-spline function (Nonogaki et. al., 2008), the region for drawing the surface is divided in M_x and M_y equally-spaced areas in x and y axis. By setting the M_x+7 and M_y+7 equally-spaced nodes, the surface is expressed by the following equation:

$$f(x,y)=\sum_{i=1}^{Mx+3}\sum_{j=1}^{My+3}c_{ij}N_i(x)N_j(y) \tag{2}$$

where $N_i(x)$ and $N_j(y)$ is the cubic B-spline function, and c_{ij} is unknown coefficient.

In order to determine the surface, objective function Q was defined as following equation:

$$Q(f;\alpha)=J(f)+\alpha R(f) \tag{3}$$

where $J(f)$ is the functional for evaluating the smoothness of the surface, $R(f)$ is the function which expresses the sufficiency degree of data, and α is the parameter balancing for these two functions. The surface is determined by substituting c_{ij} into equation (2) obtained from $\partial Q(f;\alpha)/\partial c_{ij}=0$. $J(f)$ is written by Shiono et al (2001).

The function which expresses the sufficiency, $R(f)$, is mentioned as below. The coordinate (x_p, y_p, z_p), where a measurement equipment is placed, and the measured displacement u_p has following relationship.

$$f(x_p,y_p)=z_p+u_p \tag{4}$$

Therefore, using the error average ε_p of squares between the curved surface and the obtained displacement data, $R(f)$ is evaluated as following equation.

$$R(f)=\sum\varepsilon_p^2/n_h \tag{5}$$

$$\varepsilon_p = \sum_{i=1}^{Mx+3}\sum_{j=1}^{My+3} c_{ij} N_i(x_p) N_j(y_p) - (z_p + u_p) \qquad (6)$$

where n_h is the number which satisfies equation (4).

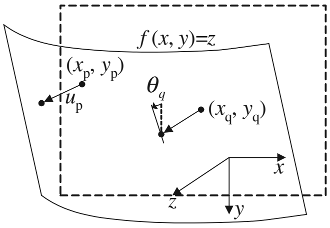


Figure 1. 3-dimensional coordinate space for drawing deformation of retaining wall

2.2 *Use of measured inclination*

In the monitoring of the retaining wall, we often measure not the displacement but the inclination because of its easiness. For this reason, it is important for developing the method to take incline data for evaluating the deformation. As follows, we show the proposed method for using the incline data.

The function *R*(*f*) is divided into two functions, $R_h(f)$ and $R_d(f)$. $R_h(f)$ expresses the sufficiency degree of displacements, and $R_d(f)$ expresses that of inclines. Using these functions, *R*(*f*) is expressed as follow equation:

$$R(f) = R_h(f) + \gamma R_d(f) \qquad (7)$$

where *γ* describes the weight of the sufficiency of inclines. $R_h(f)$ is expressed by equation (5).

On the other hand, $R_d(f)$ is defined as follows. At the position where an inclinometer located, (x_q, y_q, z_q), the derivative of the function *f* is described by the following equation.

$$f_y(x_q, y_q) = -\tan\theta_q \qquad (8)$$

Therefore, the functional $R_d(f)$ is expressed as following equation:

$$R_d(f) = \sum^{n_d}\left\{\sum_{i=1}^{Mx+3}\sum_{j=1}^{My+3} c_{ij} N_i(x) N_j(y) + \tan\theta_q\right\}^2 \Big/ n_d \qquad (9)$$

where n_d is the number of the obtained incline data.

3 SIMULATION OF LOADING TEST OF MODEL WALL

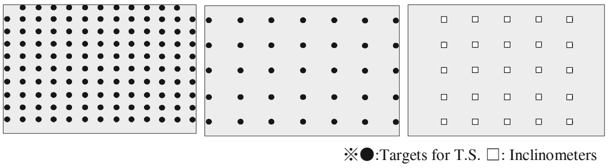
3.1 *Loading test of model wall*

Figure 2 shows the photograph of loading test. The wall was 2m in height, 3m in width and 10mm in thickness. The loading was conducted for several cases, changing boundary conditions and displacement. During the loading, the displacement and the incline of the wall were measured using a lot of measurement equipments. In the following simulation, we used only the data obtained from the survey by total station (T.S.) and inclinometers.

Figure 2. Loading test of model wall.

3.2 *Conditions of simulation*

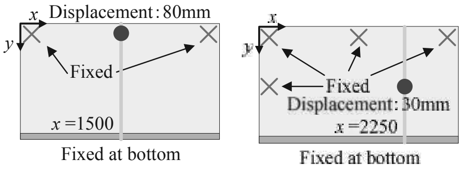
Figure 3 shows the arrangement of measurement equipments used in the simulations. (a) is the arrangement using all 128 points for the survey by T.S., (b) is using only 35 points, and (c) is using 25 inclinometers. Figure 9 shows the pattern of loading.



(a) 128 targets for T.S. (b) 35 targets for T.S. (c) 25 inclinometers

Figure 3. Arrangement of measuring points used in simulations

Figure 4 shows the arrangement of measurement equipments used in this simulation. In CASE1, 80 mm displacement was given at the top center of the wall. In CASE2, 30 mm displacement was given at the right middle part.

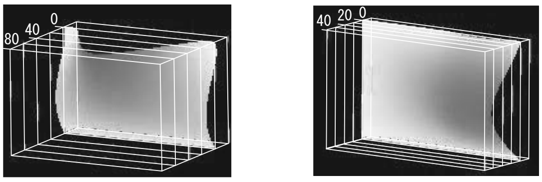


(a) CASE1 (b) CASE2

Figure 4. Loading cases used in simulation

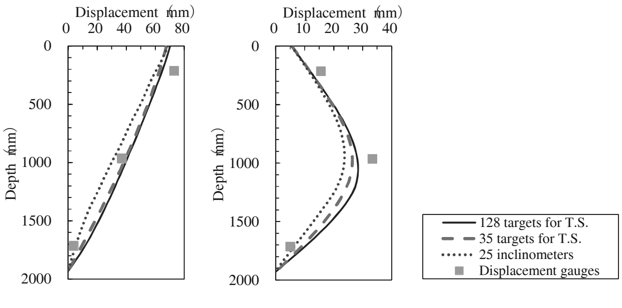
3.3 *Results of simulation*

Figure 5 shows the simulated and visualized surface using 128 points for T.S. (arrangement (a) as shown in figure 3) in both loading cases. Figure 6 shows the distributions of displacement at the cross section shown in figure 4, in both loading cases. In figure 5, displacement obtained from the contact-type displacement gauges was also plotted. From these figures, it is seemed to be that the simulation could describe the deformed surface in 3-dimension. Furthermore, the simulated displacement for each case almost coincides with measured results using the cross-section displacement gauges, regardless of arrangements or kind of used measurement equipments.



(a) CASE1 (b) CASE2

Figure 5. Evaluated and visualized deformations of wall.



(a) CASE1 (b) CASE2

Figure 6. Distributions of displacement at cross section.

From these results, it was revealed that the developed method was suitable for the evaluation and visualization of the deformation of earth retaining wall.

4 ADOPTATION OF PUROPOSED METHOD FOR FIELD MEASUREMENT

4.1 *Field condition of construction and measurement*

Figure 7 shows the field conditions of construction and arrangement of measurement equipment. The excavating work was conducted 39 m times 16 m in area, and 9 m in depth. The surface layer of the ground was a very soft alluvial clay layer about 13m in thickness, with a small N-value of SPT, followed by a gravel layer. The type of the retaining walls was bracing method. The materials of the walls were steel sheet piles. The excavation consisted of three steps as shown in figure 7.

Monitoring the wall was conducted at the south section in order to keep safe the existing tunnel for cars. Monitoring was implemented by multi-element inclinometers. As shown in figure 7, there were four survey lines and six inclinometers were set on each line. For checking monitoring data, the survey of the displacement of the wall using the total station was also conducted at regular intervals around Line No.1 and Line No.2.

Evaluating and visualizing the deformation of the wall in 3-dimensional space was conducted in the region about 33.4m in width. Two arrangements of the measurement equipments were considered. CASE1 was the arrangement using only 24 multi-element inclinometers. CASE2 was using not only inclinometers but also the displacement obtained from the survey using T.S.

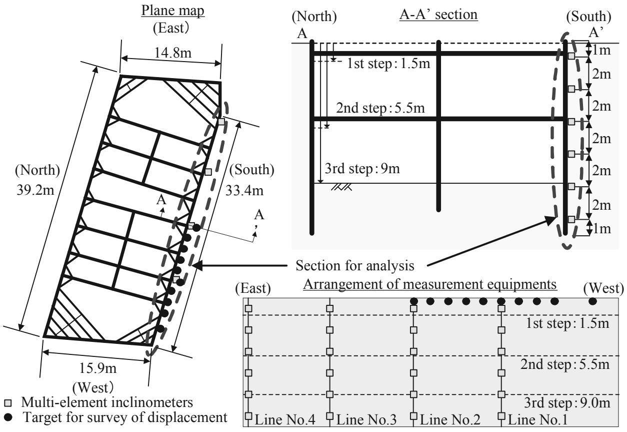
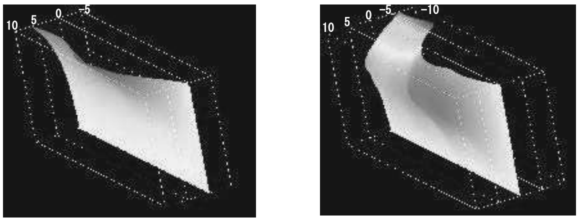


Figure 7. Conditions of field construction and measurement.

4.2 *3-dimensional evaluation and visualization of deformation of retaining wall*

Figure 8 shows the deformed wall which was evaluated and visualized after conducted excavation at each step in CASE1. From the beginning to the end of the work, the deformation of the wall was represented satisfactorily as 3-dimensional surface. The deformation was increased as the progress of the excavating work. On the other hand, as the progress, the depth where the maximum displacement occurred at deeper depth and the deformation close to the ground level was decreased due to the influence of the reaction force by installing braces.

Figure 9 shows the distributions of deformation at the cross section No.1 and No.4 as shown in figure 7. In this figure, we also showed the displacement converted from the angle obtained from inclinometers and the distances between two inclinometers, and the displacements obtained from the survey by T.S. The distributions of displacement evaluated by proposed method coincides with the mode of directly measured deformation. The displacement obtained from the proposed method was more smoothed. Furthermore, the distributions of displacement were changed largely depending on use of results obtained from survey by T.S. In this simulation, this tendency was dramatic at section No.1, where lots of targets for survey of T.S. were located. The displacement evaluated using the targets changed toward the displacement obtained from the survey at the top of the wall.



(a) 1st step (b) 2nd step

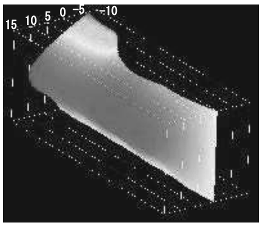
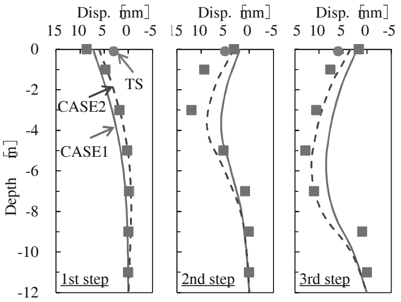
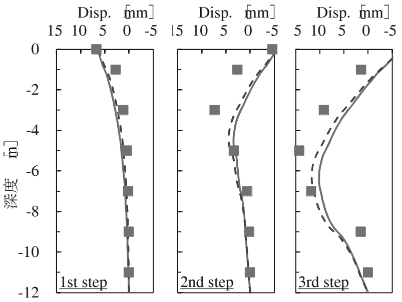


Figure 8. Deformation of wall at each step (c) 3rd step



(a)Line No.1



(b)Line No.4

Figure 9. Distributions of displacement at cross section.

From these results, the proposed method was proved to be beneficial for field measurement.

5 ADOPTATION OF PROPOSED METHOD FOR FIELD MEASUREMENT

From the study mentioned in previous sections, the validity of the proposed method was confirmed. The advantage of this method is that the data obtained from inclinometers is useful without converting to displacement. So, we can conduct the measurement using convenient inclinometers without making survey line. Therefore, by combining the proposed method and simple inclinometers, we would be able to realize precise and not expensive measurement. However, there are some problems in this method.

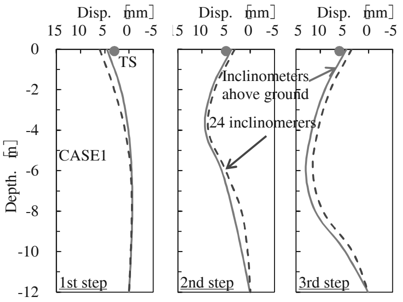
5.1 *Study of using data only upper ground*

For the measurement using convenient inclinometers, it seems to be difficult to set inclinometers under the ground. The inclinometers will be set as the progress of excavating work. So, in the case only using the inclinometers located above the ground, we studied the difference from the deformation evaluated by using all inclinometers, based on the field data mentioned in the previous section.

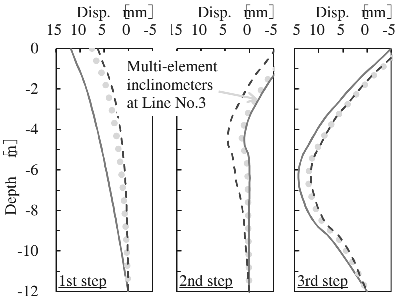
The number of used inclinometers in this simulation is 4 at 1st step, 12 at 2nd step and 20 at 3rd step. In this simulation, the data obtained from the survey using T.S. was also considered from 1st step.

Figure 10 shows the distributions of the displacement of the wall. The displacement at Line No.1 was quite similar with the one using all inclinometers, CASE1 in previous chapter. On the other hand, the displacement at Line No.4 was quite different because the direct measurement of displacement by T.S. was not conducted around Line No.4. So, we also simulated the monitoring case using multi-element inclinometers were added at Line No.3. The displacement almost coincided with the results using all inclinometers.

In monitoring of field excavating work, direct measurement of displacement or installation of one line for multi-inclinometers would enable the measurement using convenient inclinometers.



(a)Line No.1



(b)Line No.4

Figure 10. Distributions of displacement at cross section.

5.2 *Study of optimal arrangement of convenient inclinometers*

Finding optimal arrangement for conventional inclinometers would be executed by evaluating of degree of accuracy and choosing the most suitable surface for all considerable arrangements. Therefore, we conducted the simulation the accuracy of evaluated surface by iterative calculation.

Monte Carlo approach was adopted for iterative calculation and the number of iteration was 1000. The step of excavating work selected for calculation was 3rd step. For the simulation, the surface was evaluated by 8 inclinometers selected from 20 ones above the ground at random.

Figure 11 showed the obtained histogram. The horizontal axis is the evaluated average difference (Matsumaru et. al., 2011) from the surface simulated by using all inclinometers. It was revealed that the accuracy of evaluated deformation of the wall changed largely depending on the arrangement of inclinometers. However, the minimum of the difference was smaller than 1 mm. This mentioned that the monitoring using small number of measurement equipments had the possibility to maintain the accuracy of measurement depending on the arrangement. By conducting iterative calculation about considerable arrangement, the optimal arrangement would be realize.

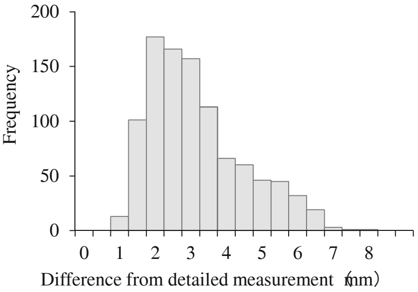


Figure 11. Histogram of average difference for considerable arrangements.

6 CONCLUSIONS

The purpose of this paper was system to evaluate and visualize deformation of retaining wall as three-dimensional curved surface. As the results, we achieved the following conclusions:

1. We developed a system adopting the cubic B-spline function as analytical technique and also proposed a method to evaluate inclinometer data as surface without transform inclines into displacements. The validity of the method was confirmed by the simulation of the loading tests of the model wall, because correct surfaces were droved using a small amount of data of displacement or using only inclines.
2. The adequacy of the proposed system was examined by applying this method to measurement of the field site of excavating work. From the beginning to the end of the work, the deformation of the wall was represented satisfactorily as three-dimensional surface. Furthermore, it was revealed that the evaluated deformation of the wall coincided with the surveyed displacement by the total station.
3. In order to realize easy monitoring of retaining walls, we checked the arrangement of inclinometers. By using the inclinometers installed above the excavation bottom, the deformation of the wall could be described almost in the same way as by all inclinometers. Furthermore, we checked the validity of the arrangement with smaller number of inclinometers by Monte Carlo approach. Though the evaluated deformation of the wall using smaller number of inclinometers was varied widely, the accuracy of the optimal arrangement was close to the one using all inclinometers.

7 ACKNOWLEDGEMENTS

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8 REFERENCES

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