Improved TDR Deformation Monitoring by Integrating Centrifuge Physical Modelling

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ABSTRACT

Landslide monitoring is the most critical challenging issue especially in the mountain where is difficult for installation of the monitoring system because of complex topography and geography. Landslide monitoring techniques include not only satellite images analysis and Global position system (GPS) for the land surface target, but also the underground methods such as inclinometer and Time Domain Reflectometry (TDR). Despite providing the early warning with a continuous displacement of the slope surface, GPS applied in landslide monitoring still exists a limitation on indicating higher accuracy and localizing the shear plane in depth. On the other hand, TDR as a warning system in landslide monitoring underground has been validated with different field studies. TDR involves continuously detecting shear surface and exactly identifying shear deformity. Although previous studies of laboratory tests have quantified shear displacement based on the TDR reflection coefficient, TDR suffers challenges for precise quantification of shear displacement from the reflection coefficient influenced by several factors, and it relatively insensitive due to artificial overburden pressure in the laboratory test. To address the abovementioned problems, this study proposed TDR integrated with centrifuge reverse fault modeling to simulate sliding at depth. To fit the centrifuge test scale, a flexible and small diameter coaxial cable was first modified and evaluated with the simple direct shear test. Then the reverse fault modeling was used to simulate the shear plane in the centrifuge modelling at the different earth gravity level. The prototype model can investigate through the 1/N scale model by enhancing the N time level earth gravity field. As testing results, this study carries out three main major parts. First, the laboratory direct shear testing showed the modified coaxial cable has dramatic improvement in the sensitivity at very small-scale shear displacement at 0.5 mm. Second, in the centrifuge physical model, the shear plane can be generated by reverse fault modeling with shear bandwidth and large shear displacement, and the quantification of the correlation between the TDR waveform and shear deformation was accordingly revealed. The quantification was further analyzed based on two methods including the peak reflection and the integration area with corresponding shear deformation. Finally, general guidelines for TDR landslide modeling in centrifuge were suggested in this study.

Keywords: Time domain reflectometry, shear deformation quantification, centrifuge modelling.

1 Introduction

Landslide is one of the natural disasters, and the impact of the landslide is tremendous on our economy and human lives. Landslide is the result of the failure of massive mass movements of rock, debris, and soil, which is naturally occurring in the hazard environment accommodation of heavy rainfall and earthquake. Most of the landslides happen in Asia especially in the country locating in a varied climate change or dynamic tectonic zone. Thereby, Taiwan has a high frequency of landslide disaster due to giant typhoons, and earthquake event is another leading trigger in Taiwan mountain areas Therefore to reduce the damages of landslide to our community, monitoring landslide is the most important step to get an early warning system to reduce the damages of landslide to our community. However, Landslide monitoring is the most critical challenging issue in the mountain where area effect by the tomography and geography for installation. Furthermore, landslide monitoring techniques from different approaches include satellite images analysis, Global position system (GPS), and underground methods such as inclinometer and Time Domain Reflectometry (TDR). Despite providing the early warning with a continuous displacement of the land surface, GPS applied in landslide monitoring still exists a limitation on realizing higher accuracy and localizing the shear plane in depth. On the other hand, TDR as a warning system in landslide monitoring underground has been validated with different field studies in slope monitoring since TDR involves continuously detecting shear surface and exactly identifying shear deformity. Thus, TDR is considered as one of the suitable techniques for landslide monitoring.

TDR technique has been widely used in monitoring applications. Dowding and O'Connor (2000) used TDR combined with inclinometer techniques in one borehole for comparing TDR reflection magnitude and inclinometer incremental displacement, which helped to quantify shear deformation by using the TDR in monitoring movement. The quantification presented in the case studies in soil and rock slopes and embankments. Singer and Thuro (2006) revealed the development by using TDR for a continuous 3D-monitoring system in unstable slopes. Lin et al. (2009) used TDR and the laboratorial shear and indentation tests in quantifying shear displacement. In addition, Lin et al. (2019) used TDR in a laboratory shear test and applied the integration method and the linear regression method for quantification of the correlation between reflection coefficient and shear displacement. From above studies, TDR demonstrated the capability for quantifying shear displacement, which is feasible index as an early warning system in slope monitoring. However, TDR technique is insensitive to the slope movement with gentle cable deformation. Nevertheless, TDR suffers challenges for precise quantification of shear displacement from the reflection coefficient by several influence factors, and the laboratory test was relatively limited due to model boundary and overburden pressure.

To solve the aforementioned problems, this study proposed TDR integrated with centrifuge reverse fault modeling to simulate sliding at a prototype condition. To fit the centrifuge scale model, a flexible and small diameter coaxial cable was firstly modified and evaluated with the simple direct shear test. Then the reverse fault modeling was used to simulate the shear plane in centrifuge at different gravity levels. This model at the prototype scale can investigate through the 1/N scale model by enhancing the N time earth gravity field, and carries out two main major findings. First, the sensitivity from laboratory direct shear testing showed that the modified coaxial cable has a dramatic improvement at very small-scale shear displacement around 0.5 mm. Second, by employing the reverse fault model centrifuge physical model with TDR, quantification of the correlation between reflection coefficients and shear displacement at small displacement 2.5 mm was investigated and showed the capability in slope monitoring at the small movement. Finally, general guidelines for TDR landslide modeling in centrifuge was were suggested in this study.

2 TDR Principle

TDR principle explanation.
TDR system block and TDR mathematics expression

$$\frac{Z_P}{\sqrt{\varepsilon_r{}^*}} = \frac{In\ (\frac{b}{a})}{2\pi}\sqrt{\frac{\mu_0}{\varepsilon_0}}\frac{1}{\sqrt{\varepsilon_r{}^*}} \qquad (1)$$

$$\frac{Z_P}{\sqrt{\varepsilon_r{}^*}} = \frac{In\ (\frac{b}{a})}{2\pi}\sqrt{\frac{\mu_0}{\varepsilon_0}}\frac{1}{\sqrt{\varepsilon_r{}^*}} \qquad (2)$$

where is a geometric factor, εr is dielectric permittivity of the surrounding material, a is the diameter of inner conductor and b is the diameter of outer conductor of a coaxial cable, $\mu 0$ is permeability of vacuum, $\varepsilon 0$ is permittivity of vacuum.

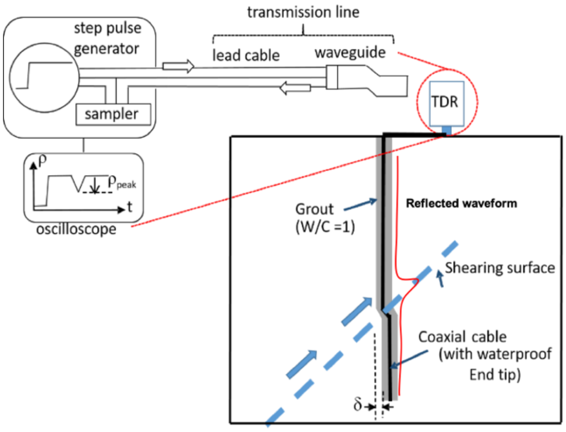
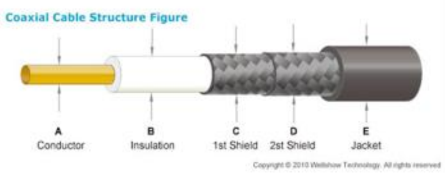


Figure1 Schematic of TDR crimp type in landslide monitoring (Chung and Lin 2019).

3 TDR Sensitivity Testing

- In the TDR sensing transmission line, (coaxial cable structure)

(a)



(b)

Figure 2 (a) Coaxial cable with 5 layers, and (b) coaxial cable with 4 layers.

- The laboratory direct shear tests to estimate the TDR sensitivity

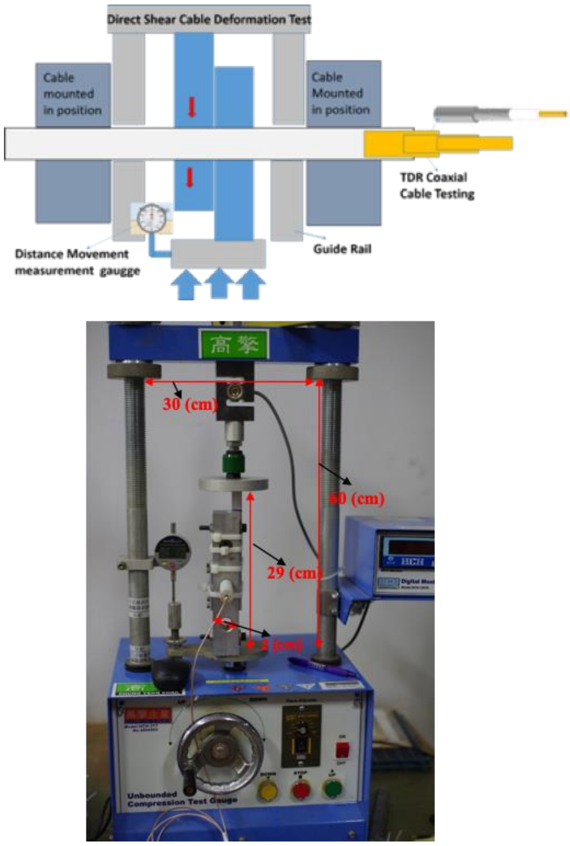


Figure 3 Schematic direct shear testing on cable grouting.

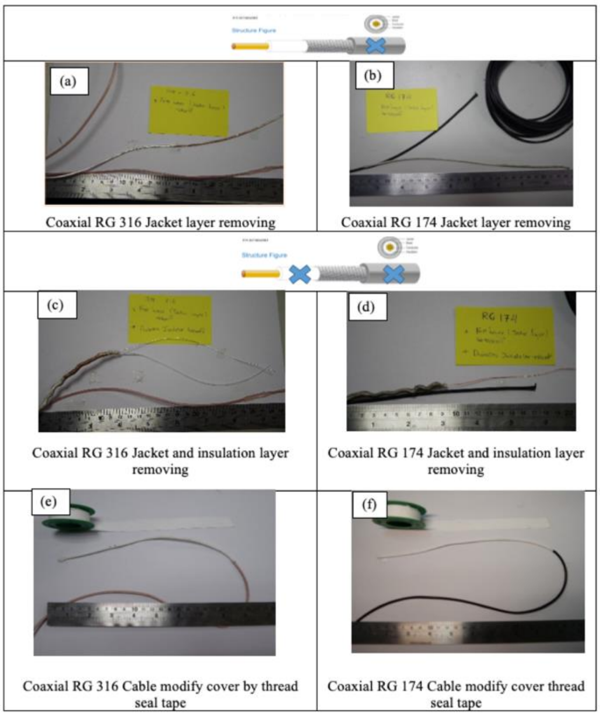


Figure 4 Coaxial cable RG174/A, and RG 316, (a), (b) the modification 1 layer replacement, (c),(d) the modification 2 layers replacement, (e), (f) cable complete cover thread seal tape.

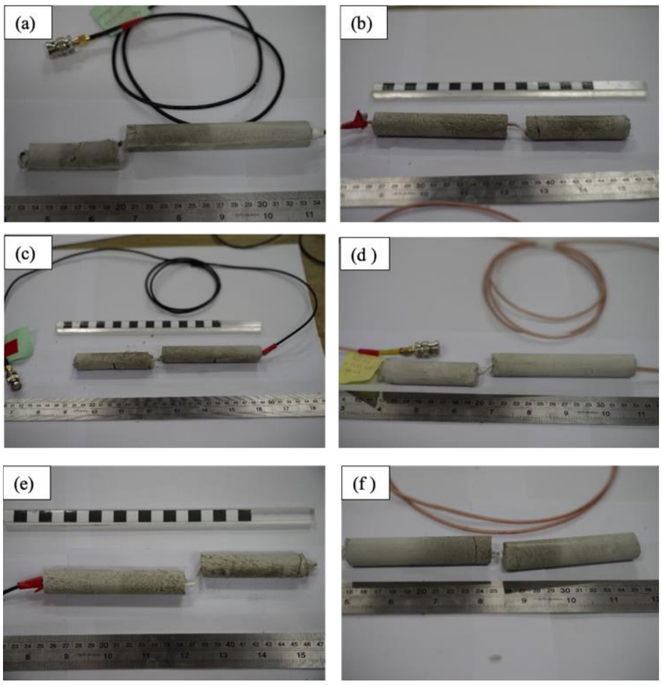


Figure 5 The original and modified of RG174/A, RG316 (a), (b) the original cable grouting and after direct shear test, (c),(d) the modified 1 layer cable grouting and after direct shear test, (e), (f) the modified 2 layers cable grouting and after direct shear test.

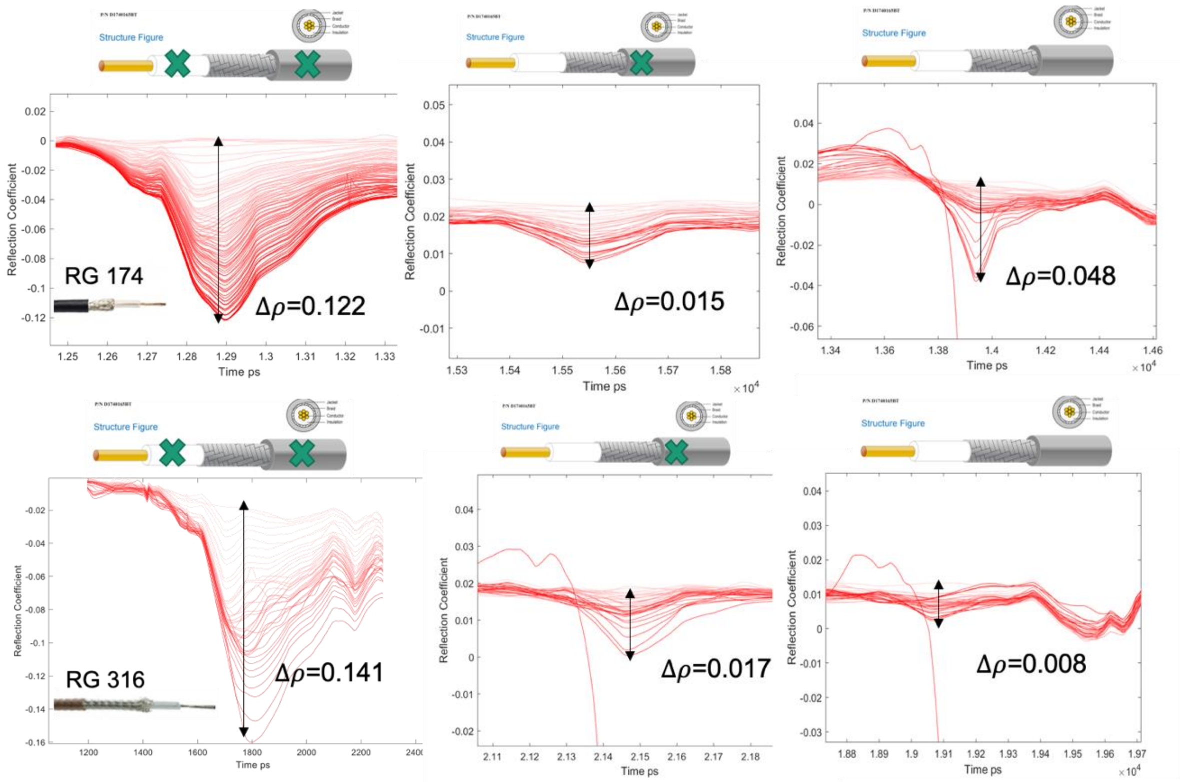


Figure.6 The zoom-in section of reflection recording caused by shear deformation (a) RG174 Cable 2 layers, modification 1 layer, and original. (b) RG316 Cable 2 layers, modification 1 layer, and original

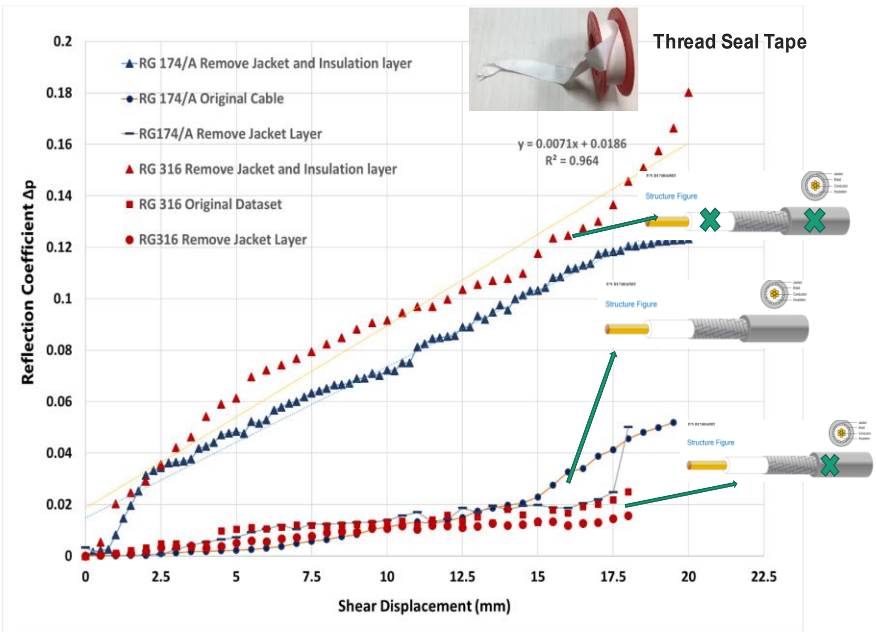


Figure.7 The correlation between reflection coefficient and shear displacement of cable RG 174/A and RG 316

4 TDR Integrate with Centrifuge Physical Model

4.1 Centrifuge Reverse Fault Model Design

- The reverse fault model at the 1g gravity condition, and The reverse fault model at 55g condition.

(a)

(b)

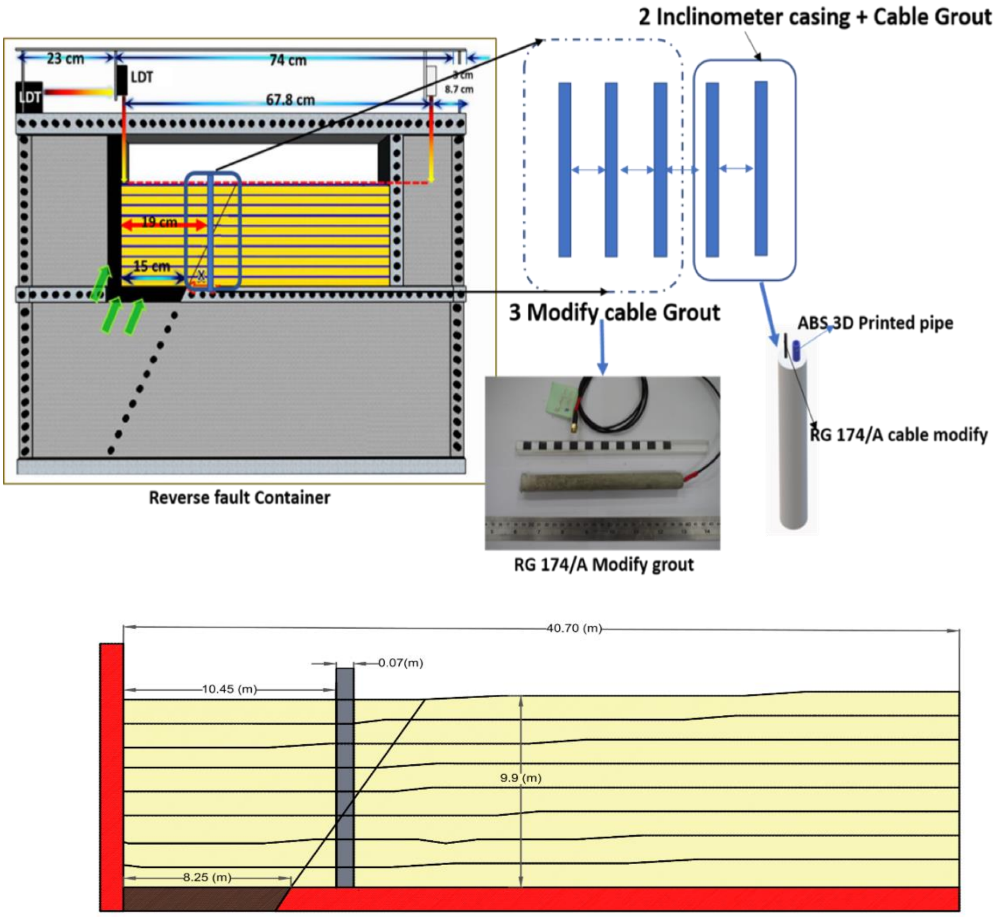


Figure.8 (a) The TDR integrate centrifuge reverse fault model 55g gravity condition configuration in scale model, (b) the 55g reverse fault model converts into the prototype model

- The grouted by the mixture of different percentage Poland cement, % Kaolin clay, and % water properties. To estimate the represent of grouting in prototype scale, the value of young modulus between the scale model in acceleration gravity and prototype model is expressed as:

$$E_{mod} \times \frac{\pi D_{mod}^4 \times N^4}{32} = E_{pro} \times \frac{\pi D_{pro}^4}{32} \quad (3)$$

where E_{mod} is scale model young modulus and D_{mod} is diameter of the model scale, N is acceleration gravity level, E_{pro} is Young modulus of prototype, D_{pro} is the diameter of the prototype model.

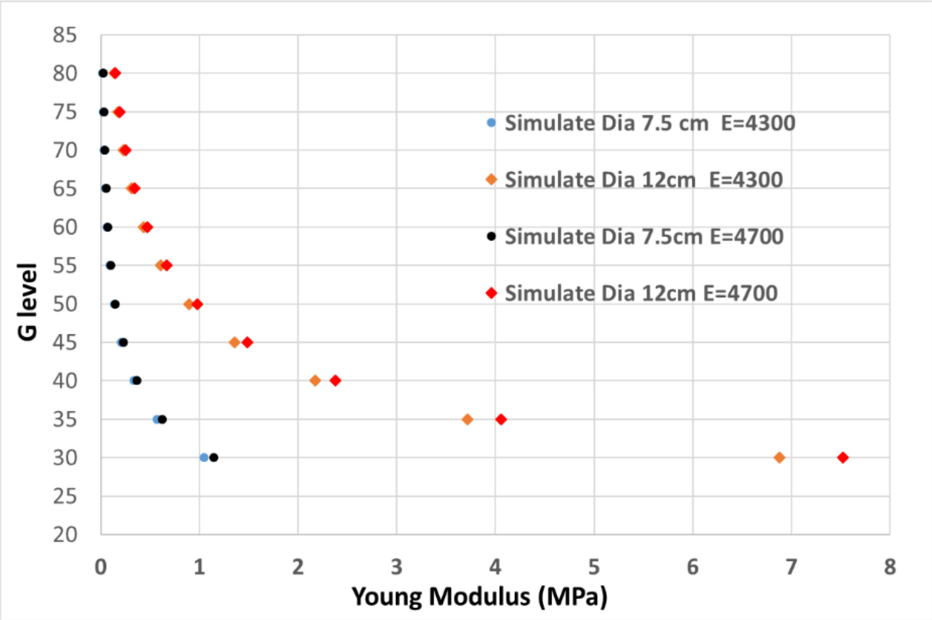


Figure 9 The young modulus of cable grouting represented the grouting in the prototype model 4300 MPa and 4700 MPa enhance by different gravity condition.

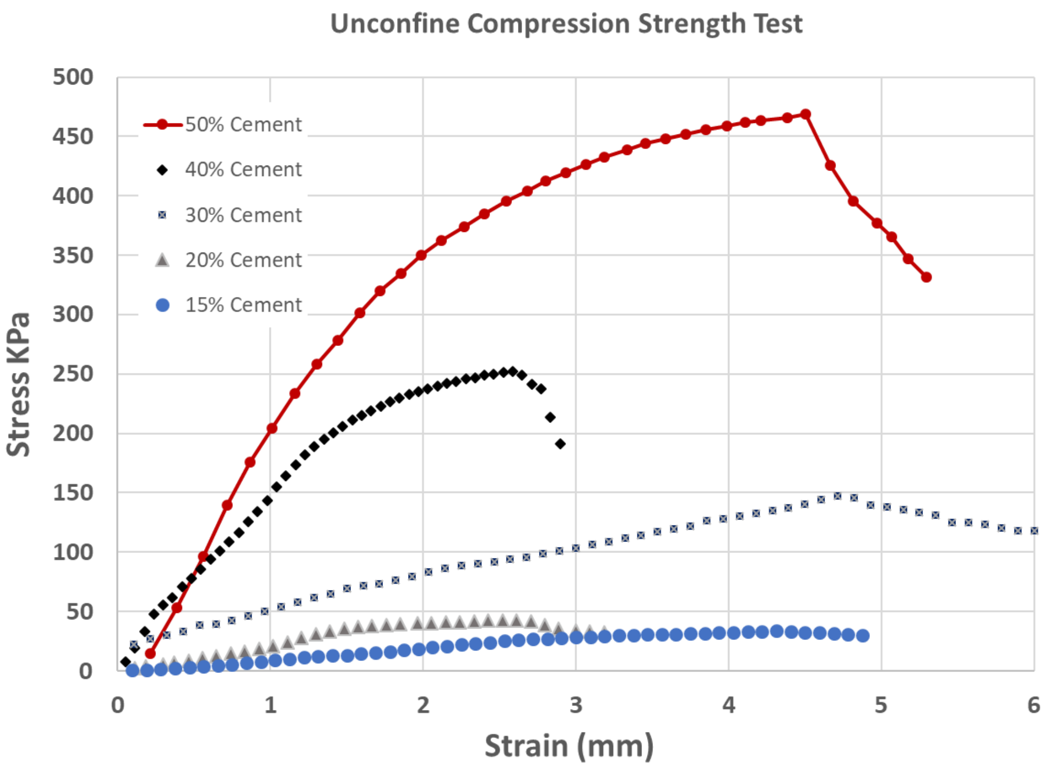


Figure 10 testing result of unconfined compressive strength test at different cement percentage.

4.1 Centrifuge Reverse Fault Model Construction and Setup

- The model construction and setup in centrifuge

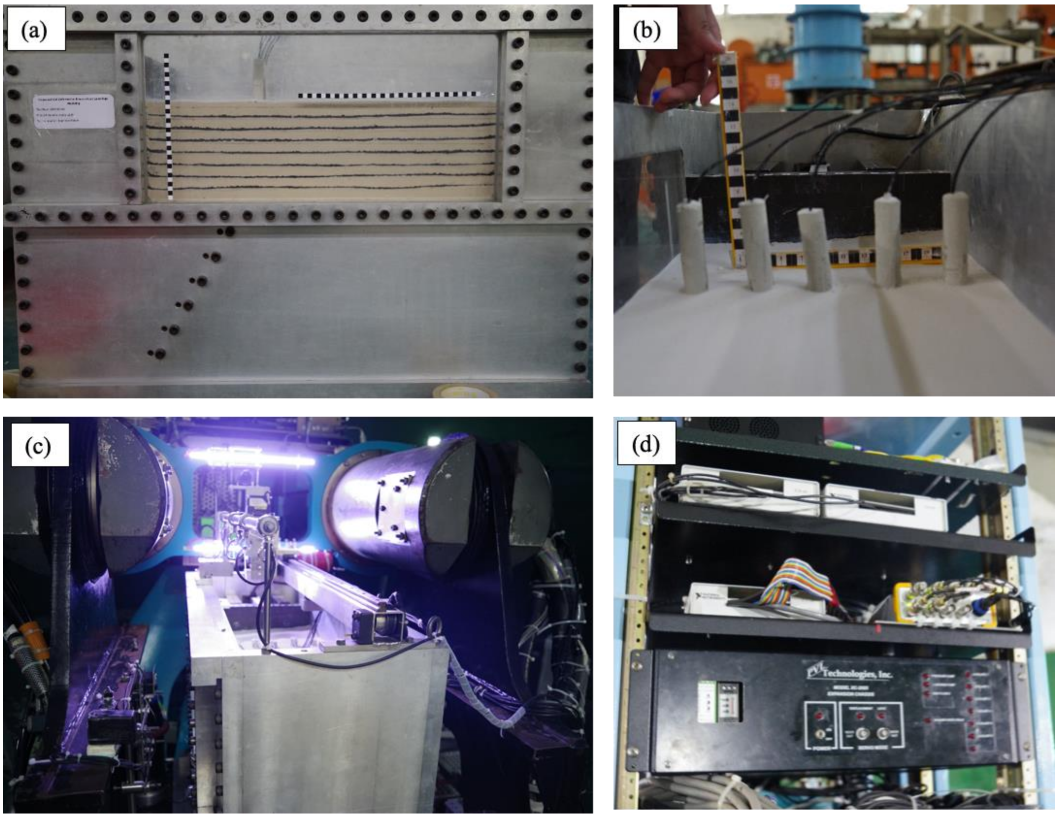


Figure. 11 (a) The completed model soil layer, (b) the cable grouting inserted inside model, (c) setting up the model in centrifuge swing platform, and (d) TDR DAQ through USB port in centrifuge system.

4.2 Testing Results and Discussion

- The profiles of the 55 g reverse fault model result.

(a)

(b)

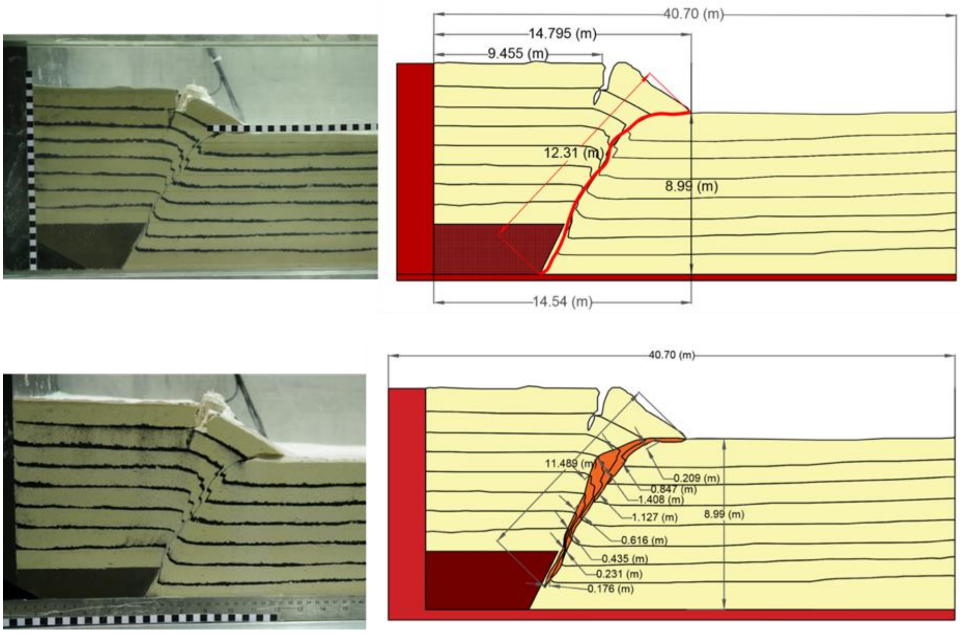


Figure.12 (a) The model shear plane generated by fault movement upward to soil layer and the model defined shear plane in prototype scale, (b) The reverse fault model shear bandwidth and shear bandwidth defined at prototype scale

(a)

(b)

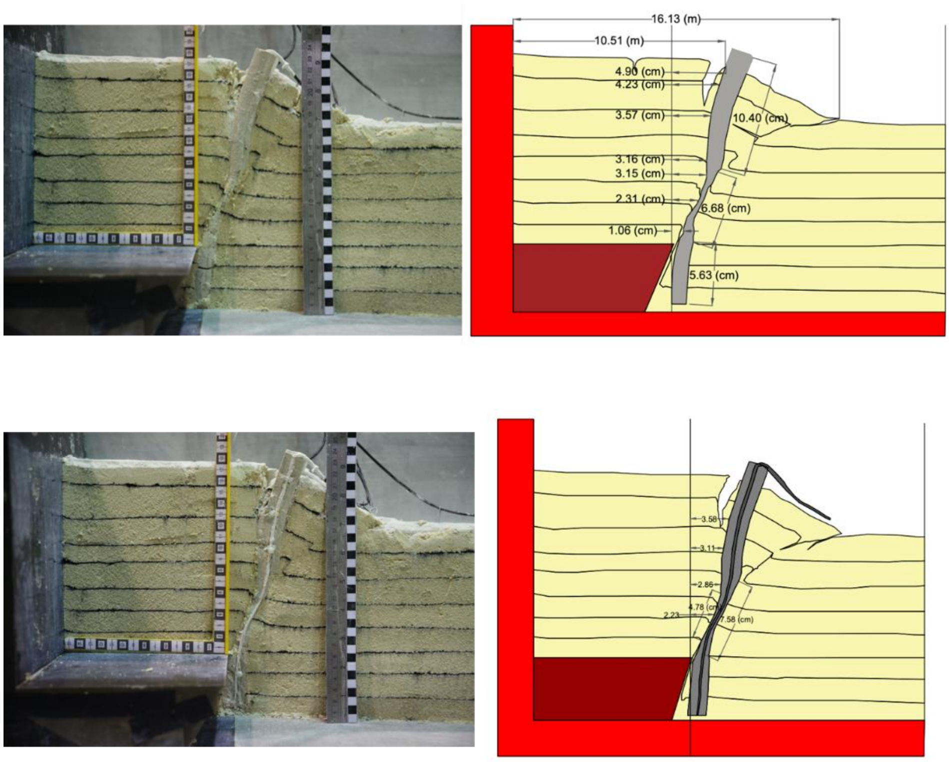


Figure.13 (a) Shear deformation created deformity and displacement to the grouting column cable 03 from model cutting profile in model scale, (b) shear deformation quantification created deformity to the cable in model scale.

Figure 13 The zoom-in section of 5 cables reflections caused by shear deformatio

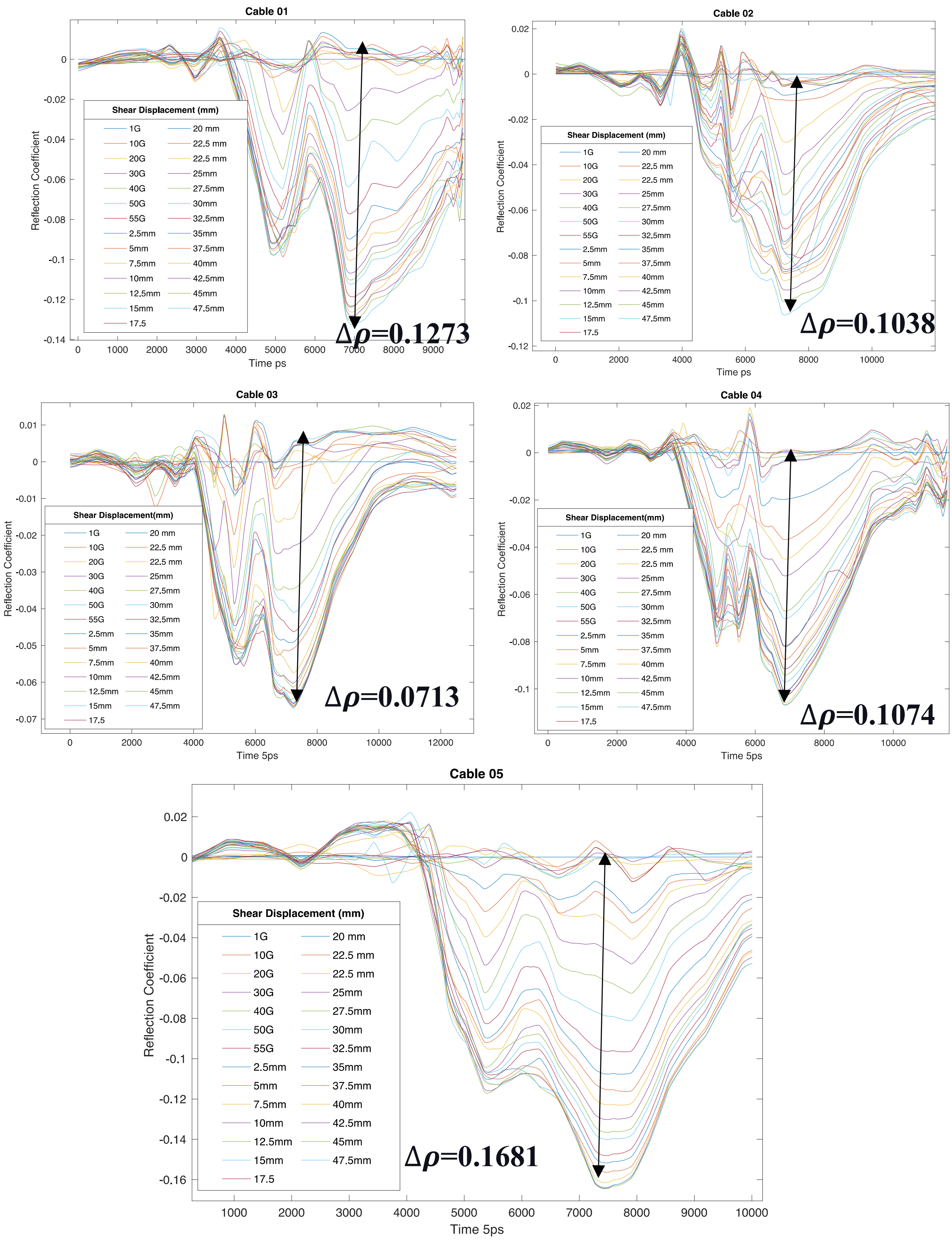


Figure 14 The zoom-in section of 5 cables reflections caused by shear deformation.

5 Quantification of Shear Displacement correlated with Reflection Coefficient

- Quantification of the correlation between TDR reflection and shear displacement. The determination of integration areas represented in the mathematic equation is expressed as. acceleration gravity and prototype model is expressed as:

$$\int_a^b f(x)dx \approx \frac{1}{2}\sum_{n=1}^{N}(X_{n+1}-X_n)[f(X_n)+f(X_{n+1}) \quad (4)$$

where $a=x_1<x_2< \ldots <x_N<x_{N+1}=b$, and $(x_{n+1}-x_n)$ is the spacing between each consecutive pair of points.

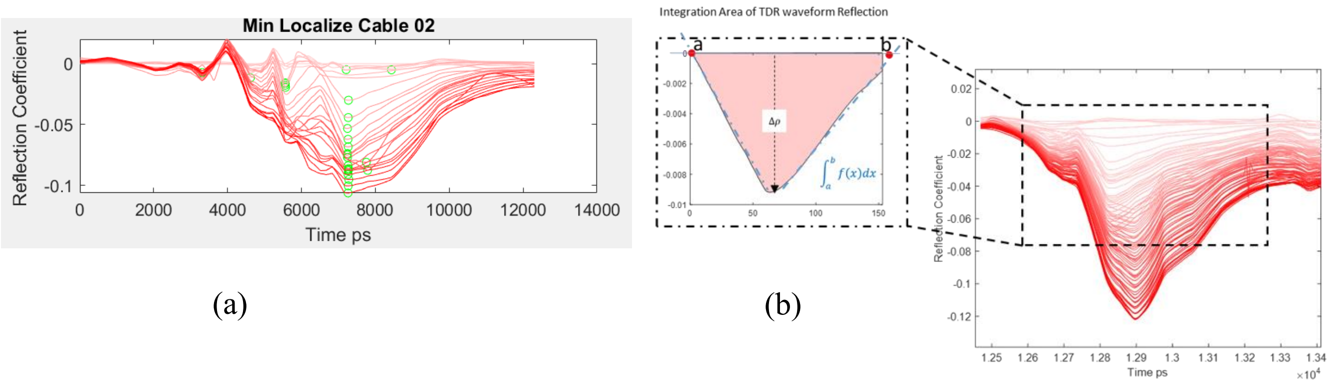
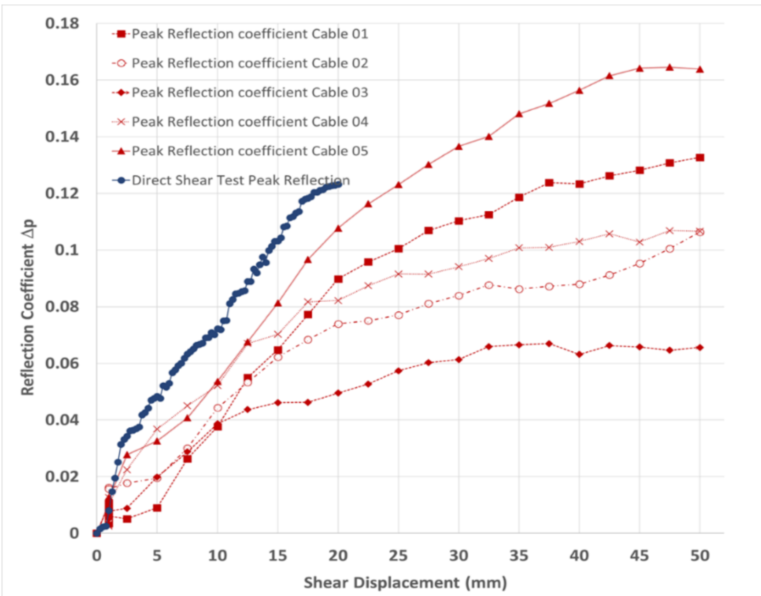


Figure. 15 (a) Determination of the peak reflection of TDR waveform at deformation section, and (b) determination of the integration areas of TDR waveform reflection.

- The comparison between direct shear test and 55 g centrifuge reverse fault model are discussed as follows.

(a)



(b)

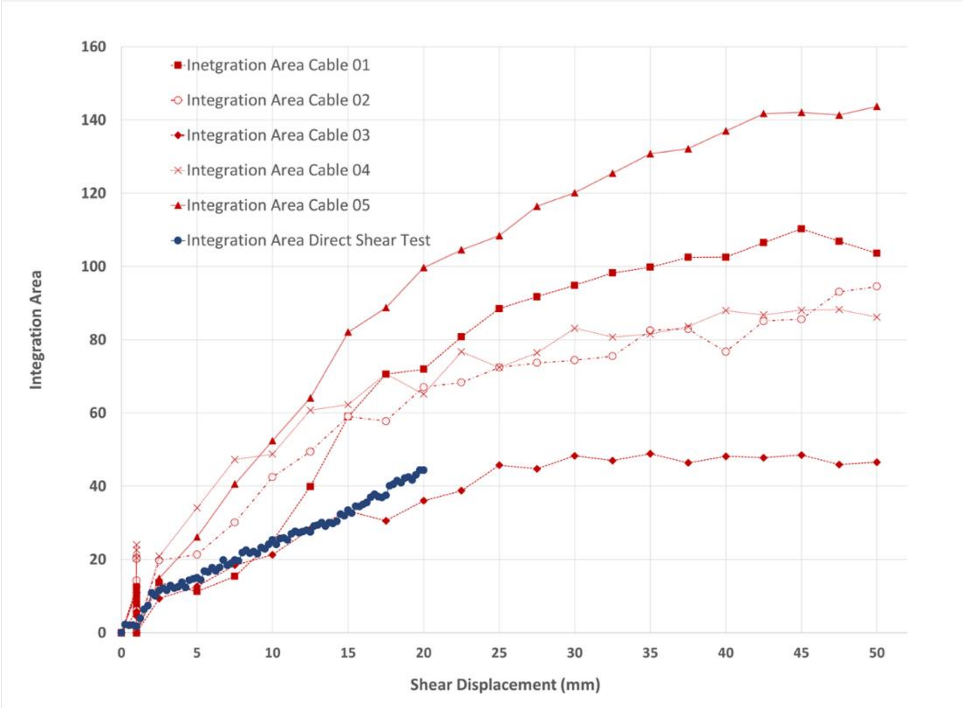


Figure.16 (a) The peak reflection coefficient correlated shear displacement direct shear test and 55 g centrifuge reverse fault of TDR waveform, (b) TDR waveform integration areas correlated shear displacement direct shear test and 55g centrifuge reverse fault.

6 Conclusion

In this study, Time domain reflectometry (TDR) was successfully used to quantify the correlation between shear deformation and TDR reflection through laboratory direct shear and centrifuge reverse fault model tests. This study's objectives are to investigate and improve TDR sensitivity in the determination and quantification pf shear deformation by providing the guideline with the TDR coaxial cable design and testing procedures in the centrifuge physical model.

1. Commercial coaxial cable was widely designed for different applications. In the TDR sensing application, the modified coaxial cable by removing the original jacket and insulation layer and replacing with the thread seal tape. This modification indicated significant improvement of TDR sensitivity in detecting and quantifying shear deformation. Furthermore, the replacing material for modification coaxial cable can be changed by other materials depending on research purposes.

2. TDR integrated into the centrifuge physical model was successful for quantifying the correlation between shear deformation and TDR waveform reflection by implementing the reverse fault model. The reverse fault model generated the shear plane by moving upward of the fault that simulated as the shear plane of the slope failure in a real case. The modified coaxial cable showed the feasibility for a small centrifuge scale model. However, the modified cable was carried out the different sensitivity in quantification of shear deformation due to the inconsistent in the replacement layers of cables. Therefore, the modified cable should be prepared carefully and consistently in replacing layers. In addition, the modified TDR cable embedding in the model with grouting carried out the better performance in localizing and quantifying shear deformation.

3. The quantification of the correlation TDR waveform and shear deformation was successfully conducted from centrifuge reverse fault test results and laboratory direct shear test result The quantification of correlation was conducted based on

two methods, including the TDR peak reflection coefficient and the integration area. Both methods indicated the better positive correlation by using quadratic regression instead of linear regression. In the direct shear test, the integration areas method was giving a better quantification of the correlation. However, in the centrifuge test, the quantification correlation between these two methods was given nearly a similar result.

4. The previous results indicated the slightly underestimated quantification of shear deformation from the laboratory direct shear test result compared to the 55 g centrifuge test by using the peak TDR waveform reflection method. Moreover, the highly overestimated quantification of shear deformation from the laboratory direct shear test results by using integration area method. When employing a laboratory direct shear test to estimate shear deformation in the real case should consider the peak of the TDR waveform instead of the integration areas because of the effect of shear bandwidth.

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