Modeling and interpretation for ground anchor failure signals under pullout loads

Modélisation et Interprétation des signaux de défaut d'ancrage au sollors de retrait des charges

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ABSTRACT

This paper discusses the modeling and interpretation for ground anchor failures under the pullout load test. A real-time acoustic monitoring technique was used in the field tests on two pre-stressed anchors. One-dimensional analytical model was established to model the anchor's behaviors. With the use of attenuation law for waves propagating at the concrete panel, the predicted signals were found comparable to the field data and the 2D/3D finite element modeling using *ABAQUS*. It was found that the analytical model could capture closely the progressive failures of the ground anchor. By analyzing the signals appearing at the concrete wall, the author suggests the use of Power spectrum density with Welch window method. With the application of short time Fourier Transform, the Hamming window is preferred. It is also found that the resulting signals are highly dependent of the failures. As the damages become more severe, the signals at the time-frequency domain as a result of the short time Fourier Transform would be more distributive.

RÉSUMÉ

Cet article traite de la modélisation et de l'interprétation des défauts d'ancrage au sol lors de test de retrait de charge. Une technique de surveillance acoustique en temps réel a été utilisée dans le cadre d?essais sur le terrain sur deux ancres précontraintes. Un modèle analytique dimensionnel a été établi pour modéliser le comportement de l'ancre.Avec l'utilisation de la loi d? atténuation desondes se propageant à la plaque de béton, les signaux anticipés étaient comparables aux données sur le terrain et à la modélisation avec ABAQUS des éléments finis en 2D/3D. Il a été constaté que le modèle analytique pouvait suivre de près la progression des défauts d'ancrage au sol. En analysant les signaux qui apparaissent dans le mur de béton, l'auteur suggère l'utilisation de la densité spectrale de puissance avec la méthode de la fenêtre Welch. Avec l?application de la transformation de Fourier de courte durée, la fenêtre de Hamming est préférable. Il aégalement été constaté que les signaux sont très dépendants desdéfauts. Au fur et à mesure que les dommages s?aggravent, les signaux au domaine temps-fréquence sont plus distributifs en raison de la transformation de Fourier de courte durée.

Keywords : ground anchor, pullout load test, acoustic monitoring, failure, signal analysis

1 INTRODUCTION

As many of slope engineering projects in Taiwan have involved with the use of ground anchors, the testing and monitoring of the ground anchors is now of more importance in geotechnical engineering practice. At the present time, there is no effective method for monitoring the anchors. Current approach is to use the pullout load test to verify the design and the residual capacities of anchors; only single and pre-equipped anchor could be tested at one time. An effective and non-destructive instrumentation system that could monitor large number of anchors and provide pre-warning function is in an urgent need.

In this regard, a demonstrating project was made by Lee et al. (2003) who acts as a landmark figure in the field pullout load tests on two ground anchors with the real-time acoustic monitoring system supplied by the PAA international engineering group. Feasibility of the proposed measurement on ground anchor reinforced slopes instead of the pre-stressed bridge slabs or tanks were reported. Result of their tests found can prove the proposed monitoring system provides an ultimate solution for monitoring slopes stabilized by large number anchors. Their research found that both the pre-stressed wire breakages and the grout slippages and the surface concrete frame cracking were captured by the monitoring during the load test. The frequency-domain spectra of the signals and consistent load-energy relationships of the progressive failures were discussed in their studies to clarify the potential use of the monitoring system. In this paper, the authors intend to introduce the testing and, further, the follow-up research study (Chang et al., 2007; Cheng et al., 2008; Chang et al., 2008) planning to simulate the pullout load test and the signal interpretations for the ground anchor monitoring system.

2 ACOUSTIC MONITORING ON ANCHOR FAILURES

The acoustic monitoring system is designed to receive the wave propagation released by the failure event. By estimating the travel speed of acoustic and the distance between the source and receiver, the location of source can then be obtained. To utilize this feature, modern technology bridges the acoustic monitoring system with the real-time monitoring system. By combining these two systems, any event that triggers an acoustic signal can be captured by the real-time acoustic monitoring system while the event is occurring. Another important character is that each type of event should have its unique acoustic signature. By differentiating each acoustic signal, this system can not only provide the location of the event, but also indicate the type of the event. The real-time acoustic monitoring system can also perform the function as the pre-warning system. The system can grasp the early events among the failure process and provide warning to the responsible authority before the real disaster occurred.

In previous experiments, the real-time acoustic monitoring system is often used in monitoring the nuclear power station or bridges, which usually constructed with the pre-stressed

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concrete and steel tendon. Figure 1 illustrates the layout of the acoustic monitoring system applied to the ground anchored structure. As to the application of the real-time acoustic monitoring system on ground anchors, a proper arrangement of the system on a pre-stressed anchor system may detect the damaged anchor in its early failure process. In addition to the location of damage, the acoustic signal of the damage event could also provide the type of damage, for example, concrete or cement cracking, deep wire breaking, and surface wire breaking.

This idea was first adopted and demonstrated by Lee et al. (2003) on monitoring on-situ anchor failures caused by the pullout test with the real-time acoustic monitoring system. The anchor system in the test filed was constructed near 1995 (see Figure 2). Besides experiment the pullout testing on the old anchor, they have also established a new non-prestressed anchor for the purpose of comparing the discrepancy between the two. The loading process produced the progressive failure scenarios in the old and new anchors are consisting of: 1. slippages between grouted and soil that produced cement cracking, 2. deep wire breakings, 3. wire breakings close to the surface of the concrete frame, 4. final pullout of the wire tendon. During the tests, each of the failure scenes was recorded in the SoundPrint® system made by Advitam. There are 13 sensors mounted on the concrete frame to collect the signals from the two anchors. The test data including the load-time curves and the anchor head displacement versus load diagram are shown in Figure 3. Clear progressive failures for the cement cracking, deep wire breakings and surface wire breakings of the anchor could be observed. The collected records were analyzed as the spectra for every event, and the received energy of these events were calculated and then taken into consideration to depict their possible applications. It was concluded that the acoustic monitoring system has great potentials in helping the engineers to understand the safety and performance of the ground anchors.

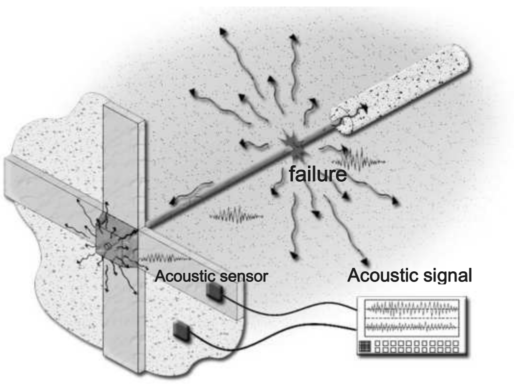

Figure 1. Layout of the acoustic monitoring anchored system

(a) Picture of test field

(b) Scheme of acoustic sensors locations and two anchors

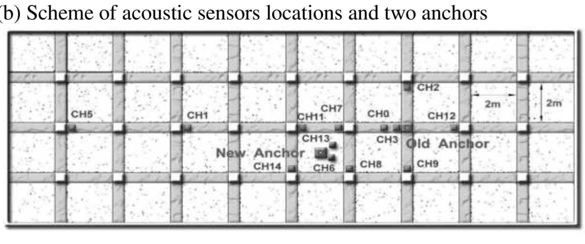

Figure 2. The field study site and acoustic sensor locations.

3 NUMERICAL MODEL

To better understand the failure sequence of the anchor subjected to the pullout load, a one-dimensional multi-degree-of-freedom ground anchor system was adopted to analyze the load-displacement relationships of the anchor (Cheng, 2009). In order to have a cautious plan in simulating the major structural elements in the failure scenarios, lumped masses, springs and dashpots are all seriously taken into account. Only the longitudinal compression-tension wave motions were hypothesized in the structural system. Similar applications of these elements were also suggested by Ivanovic et al. (2001; 2002) in modeling the signal and dynamic response of an anchorage. In their study, the characteristics of materials are presumed elastic. It focuses on the modeling of dynamic signal and the validation of non-destructive technology GRANIT (Ground Anchorage Integrity Testing) system.

Moreover, neither the destruction of anchors is reckoned nor is the immediate reaction from the ground anchors system acquired. In order to get a more reasonable simulation of the process during anchor pullout, the required models for the stress-strain and shear stress-slip relationships for these elements follows the suggestions of Duncan & Chang (1970), PCI (1997) & Cai et al., (2004).

3.1 *Pullout load test model*

Instead of time-dependence concern, the pullout load in the analysis can be considered as a stage loading function. For simplicity, the pullout load can be statically applied onto the system of equations excluding the mass and damping terms, only the spring forces are mainly considered for the structural behaviors. The load and displacement curve simulated is able to compare with the field data. Though this simplified modeling, the destructions of the elements can be clearly seen. Proper stress and strain relationships at various structural components were the keys to such analysis. In general, breaking occurs when the strain of steel tendon exceeds the yielding strain ($\varepsilon_{ps} > 0.0076$ for 250 ksi tendon ; $\varepsilon_{ps} > 0.0086$ for 270 ksi tendon); cement crack occurs when the displacement between steel tendon and soil is larger than the limited shear-slip displacement of the grout.

3.2 *Acoustic signal model*

To understand the acoustic signals triggered at the moment of destructions, this study, in accordance with the result of static analysis, preserves the material parameters to conduct the complete dynamic analysis of the discrete anchored system. A unit triangle pulse at the point of damage is generated to simulate the failure signals. The energy allocation of the signals at various failures has been discussed. For better comparisons, the load magnitude and the duration of impulse were differing at various damages to a great extent. Ration response signals can be obtained if the initial velocities of the structural system at the occurrence of failure can be carefully applied. The constant averaged acceleration scheme of the implicit integration method was adopted to obtain the solutions (Cheng, 2009).

4 SIMULATION OF FIELD TEST

To ensure the feasibility and applicability of the pullout load test prediction in this study, the author uses the design geometry and the assigned soil parameters from the field report (Cheng, 2009). After validation of the pullout test simulations, the parameters to affect the predictions and the signals compared to the finite element analysis were investigated.

4.1 *Pullout load test prediction*

Comparing the field pullout load test data with the simulation result (as shown in Figure 3), it shows that the load-displacement curve of numerical predation tallies with the occurrence order of different destruction modes and the magnitudes of the field. Because the details of the material and component failures may not be exactly the same as the filed, the timing of the destruction, the number of failures and the corresponding loads were found incompletely comply with field test. However, they are rationally agreeable. Table 1 and Table 2 are respectively the result of field test as well as numerical simulation and the comparison of failure occurrence.

4.2 *Comparative finite element analysis*

With the use of computer program ABAQUS (2006), the numerical model can automatically duplicate the mesh along the center line of tendon to the right side according to the definition of location of node. The modeling of old anchor contains 17,173 nodes and 5,508 elements. In order to accelerate the analysis, all the elements adopt CAX8R for the modeling. In the analysis, the material models are kept as same as possible with the sampled procedure, which includes: 1. nonlinear elastic model for steel tendon, 2. perfect elastic-plastic model for grout, 3. hyperbolic model for the soils.

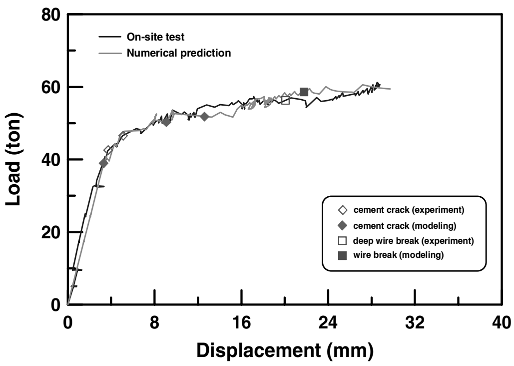

Figure 3. Comparative load-displacement relationships for numerical solutions and field data of old anchor.

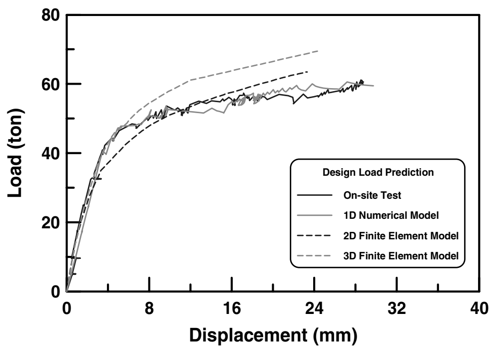

Figure 4. Comparison of load-displacement relationships for 1D modeling and 2D/3D FEM solutions with the field data.

It presents respectively the analytical domains and meshes used for old anchor and new anchor. Similarly with the ABAQUS, the old anchor contains respectively 32,217 nodes and 6,930 elements. For economic computations, all elements adopt the 20-node brick element (C3D20R) in 3D model. Same material model used in 2D ax symmetric model were used herein. Figure 4 depicts the results of the field test with the predictions from the 1D analysis and ABAQUS. It can be seen clearly that excellent agreements were able to obtain. By comparing the applicability, the characteristics and restraints, and the applications of these methods as shown in Table 4 for establishing load displacement curve of the pullout load test on ground anchors, one can find that the proposed modeling is rather economic than the two others. If material properties and model parameters were carefully controlled, then this model perhaps can have great potential in a certain subjects of ground anchor study.

Table 1. Comparison of ground anchor field test and numerical results.

Item	On-site test	Numerical Model
Design load (tons)	48.0	48.0
Failure events	3	4
Final failure mode	fall apart	final rupture

Table 2. Comparison of ground anchor failure from the field test and numerical modeling.

On-site test		Numerical Model	
Load (tons)	Failure events	Load (tons)	Failure events
42.79	cement crack	38.88	cement crack
46.57	cement crack	50.25	cement crack
–	–	51.91	cement crack
57.58	deep wire break	58.41	wire break (4~5m)

4.3 *Simulation of acoustic signal*

To prove the simulation effect of analytical signals, the author have analyzed the experimental acoustic signals first (see Cheng, 2009) to understand the surface energy allocation of anchor elements at the moment when failures occur. The field signals were recorded as the record of accelerometers using Piezoelectric Crystal. Plotting them with limited amplitude of 10 volts, the predicted accelerations can be compared to these signals with proper calibrations. For the sake of convenience to compare with the experimental signals, the modeling result can adopt a constant value (old anchor : 1.5×10^{7} ; new anchor : 4.0×10^{6}). The resulting amplitudes are in the order of 10 mm/sec^2. In Figure 5 where the first failure event of the old presents, the entire duration and magnification of parts of concrete frame indicate that analytical signals and experiment signals are similar in a certain sense.

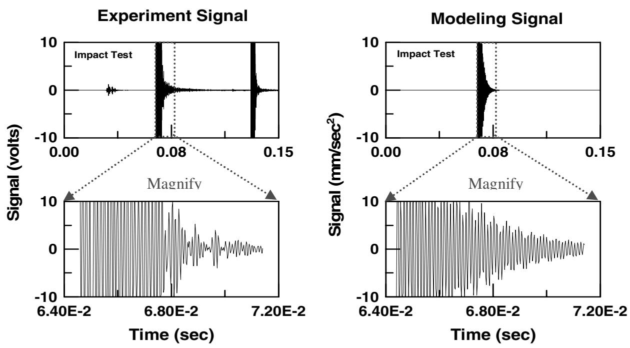

Figure 5. Comparison of experiment signal and modeling signal for anchor failure even.

It should be pointed out that without the restraint of anchor head (which is currently limited in the modeling), the 1D analysis can only simulate the first arrival of the failure signals. It cannot acquire the signal reflections.

4.4 *Signal interpretation*

A number of signal analyses have been studied for better data interpretation. Correlation relations, FFT, Power Spectrum Density and Short-time FT were conducted. Figure 6 depicts a failure signal from the Power Spectrum analysis with various windows. It can be seen that the Welch window can provide more clear signals than others. On the other hand, the Figure 7 shows the time-frequency plot of the same signals from the

Short-time FT with the use of Hamming window. This analysis can reveal the signal information more closely by comparing them as the consequent results of the damages. As the damage became more severe, the signal tends to be more distributive at the time-frequency domains. Figure 8 shows the comparison of the testing signals and the predicted signals from numerical modeling. It can be seen that the significant frequency corresponding to peak of the signals will drop slightly as the failures progressed. The test and numerical results are agreeable.

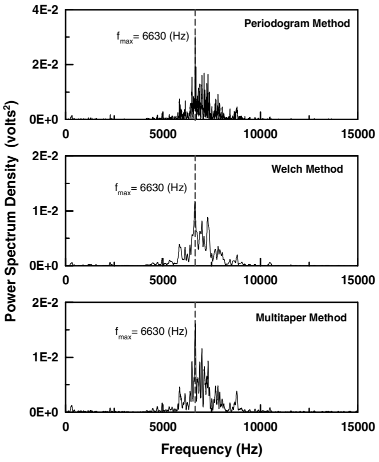

Figure 6. Comparison of failure signal from the Power Spectrum analysis with various windows.

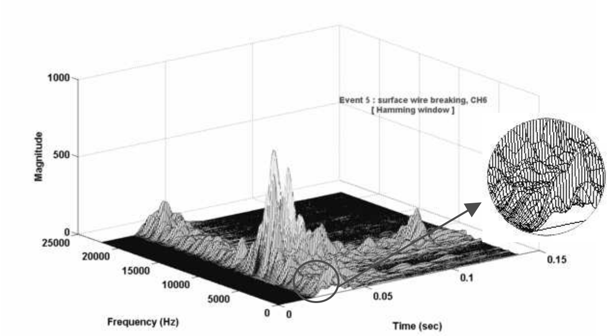

Figure 7. Signal amplitudes from short-time FT analysis

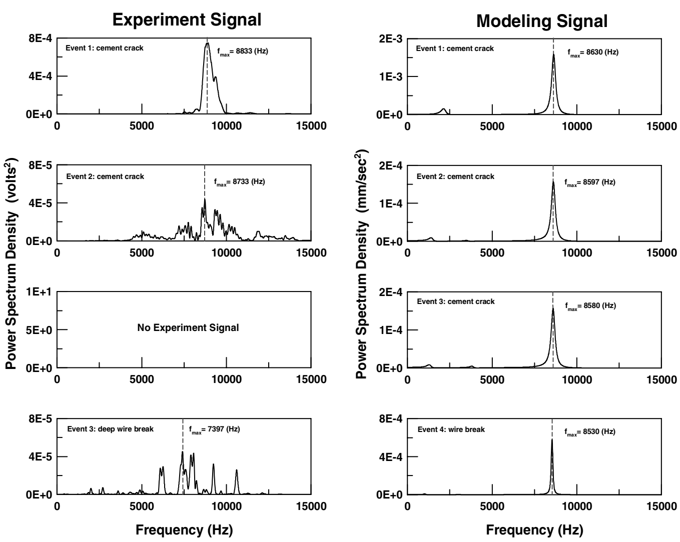

Figure 8. Comparisons of signals from test and numerical modeling for progressive failures

5 CONCLUDING REMARKS

One dimensional model suggested in this study can be used to simulate the pullout test of the ground anchor. The acoustic signals occurring at the anchor failures can be captured through the impulse analysis conducted after the static modeling. The conclusions are withdrawn as follows:

(1) The suggested modeling is proven to be a feasible solution, and it can confirm the field interpretations of anchor failures.

(2) The results of anchor failures are similar to field test results, practiced by first cement crack and then wire break. Rational deviations of the number of occurrence, and the load and time where the damages occurred can be seen.

(3) It is rather convenient to use the 1D analysis with the attenuation law of concrete to simulate the signals recorded in the concrete panel. The solution is rather convenient and fast enough when serving as the core as in the inversion or back analysis of the field signals.

(4) The acoustic signal modeling suggested that the present study can only obtain the first arrival of the failure signals. The signal reflections are however unable to reveal because the nature of lumped mass analysis.

(5) Power spectrum with the Welch window method is suitable for frequency spectrum analysis. Short time Fourier Transform w/ the Hamming window is preferred for time-frequency analysis of the signals. Resulting signals are highly dependent of the failures. As the damages become more severe, the signals at the time-frequency domain are more distributive.

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